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Dissociating retrieval interference and reanalysis in the P600 during sentence comprehension

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Abstract

We investigated the relative independence of two key processes in language comprehension, as reflected in the P600 ERP component. Numerous studies have linked the P600 to sentence- or message-level reanalysis; however, much research has shown that skilled, cue-based memory retrieval operations are also important to successful language processing. Our goal was to identify whether these cue-based retrieval operations are part of the reanalysis processes indexed by the P600. To this end, participants read sentences that were either grammatical or ungrammatical via subject-verb agreement violations, and in which there was either no possibility for retrieval interference or there was an attractor noun interfering with the computation of subject-verb agreement (e.g., "The slogan on the political poster(s) was/were . . ."). A stimulus onset asynchrony manipulation (fast, medium, or slow presentation rate) was designed to modulate participants' ability to engage in reanalysis processes. Results showed a reliable attraction interference effect, indexed by reduced behavioral sensitivity to ungrammaticalities and P600 amplitudes when there was an opportunity for retrieval interference, as well as an effect of presentation rate, with reduced behavioral sensitivity and smaller P600 effects at faster presentation rates. Importantly, there was no interaction between the two, suggesting that retrieval interference and sentence-level reanalysis processes indexed by the P600 can be neurocognitively distinct processes.

Descriptors: P600, Sentence processing, Cue-based retrieval, Agreement attraction, Reanalysis

Successful sentence comprehension is a tremendously complex task, requiring the processing of numerous types of information (e.g., orthographic, phonological, semantic, syntactic) with amazing speed. Given the temporal demands and information load inherent in sentence processing, numerous component processes must be engaged in order to achieve comprehension. In the present work, we investigate the relationship between two key processes involved in language comprehension—reanalysis and memory retrieval—as reflected in ERP measures. Electrophysiological examinations of sentence comprehension have typically focused on two ERP components, the N400 and P600. Whereas the N400 is modulated by factors related to the ability to anticipate, access, and/or integrate lexical and semantic information (e.g., Federmeier & Kutas, 1999; Federmeier, Wlotko, De Ochoa-Dewald, & Kutas, 2007; Kutas & Hillyard, 1980, 1984; Van Berkum, Hagoort, & Brown, 1999; Wlotko & Federmeier, 2012, 2015), the P600 effect is elicited by a broad range of semantic and syntactic manipulations.

A number of studies have reported that syntactically and morphosyntactically anomalous words elicit a P600 effect (e.g., Friederici, Hahne, & Mecklinger, 1996; Hagoort, Brown, & Groothusen, 1993; Hagoort, Wassenaar, & Brown, 2003; Mehravari, Tanner, Wampler, Valentine, & Osterhout, 2015; Osterhout & Holcomb, 1992; Osterhout & Mobley, 1995; Tanner & Bulkes, 2015), as do some words in well-formed but complex sentences (e.g., garden path sentences: Gouvea, Phillips, Kazanina, & Poeppel, 2010; Kaan & Swaab, 2003; Osterhout, Holcomb, & Swinney, 1994). This set of syntax-related findings led some to argue that the P600 reflects essentially syntactic processes (e.g., Allen, Badecker, & Osterhout, 2003; Gouvea et al., 2010; Kos, Vosse, van den Brink, & Hagoort, 2010; Osterhout, Mckinnon, Bersick, & Corey, 1996; Osterhout & Nicol, 1999). However, recent work has also found P600 effects in response to a broad range of nonsyntactic manipulations, including highly semantically anomalous sentences, sentences with animacy violations, or sentences with thematic role violations (e.g., Chow & Phillips, 2013; DeLong, Quante, & Kutas, 2014; Hoeks, Stowe, & Doedens, 2004; Kim & Osterhout, 2005; Kim & Sikos, 2011; Kuperberg, Caplan, Sitnikova, Eddy, & Holcomb, 2006; Kuperberg, Kreher, Sitnikova, Caplan, & Holcomb, 2007;

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van de Meerendonk, Kolk, Vissers, & Chwilla, 2010; see Van Petten & Luka, 2012, for a review), as well as nonlinguistic manipulations involving musical syntax (e.g., Patel, 2003; Patel, Gibson, Ratner, Besson, & Holcomb, 1998).

These reports of nonsyntactic P600 effects have led to a set of nonmutually exclusive proposals regarding the functional nature of the P600. These include (a) continued combinatorial processing following violations of morphosyntactic and combinatorial constraints or following conflicts between the outputs of memory- and constraint-based processing streams and integration of real-world event knowledge (Kuperberg, 2007; Paczynski & Kuperberg, 2012), (b) engagement of conflict-monitoring mechanisms in response to inputs that strongly conflict with top-down expectations or when the outputs of a heuristic and algorithmic processing stream clash (Kolk & Chwilla, 2007; van de Meerendonk, Indefrey, Chwilla, & Kolk, 2011; van de Meerendonk et al., 2010), (c) a failed mapping between animacy/thematic roles and plausibility followed by well-formedness checking (Bornkessel-Schlesewsky & Schlesewsky, 2008), or (d) continued difficulty with semantic interpretation following anomalous input (Brouwer, Fitz, & Hoeks, 2012). What is common among these more recent proposals is that they place the P600 not in the domain of core morphosyntax, but instead in a late stage of processing where multiple bottom-up information sources (syntactic, semantic, thematic, orthographic, etc.) are integrated and evaluated with respect to top-down expectations. That is, all of the aforementioned models posit that the P600 is triggered by processes involving attempts to reconcile multiple mismatching representations in memory. We will use the term *reanalysis* to refer generally to this set of processes.[1]

However, fundamental questions remain about the relationship between the reanalysis-related P600 and other key processes involved in sentence comprehension. One such process is memory retrieval. Many recent models of sentence processing invoke cue-based memory retrieval as a core mechanism in sentence processing and, in particular, the establishment of long-distance linguistic dependencies (Lewis & Vasishth, 2005; Lewis, Vasishth, & Van Dyke, 2006; Martin & McElree, 2008; McElree, Foraker, & Dyer, 2003; Van Dyke, 2007; Van Dyke & Johns, 2012; Van Dyke, Johns, & Kukona, 2014; Van Dyke & McElree, 2006; Vasishth, Brüssow, Lewis, & Drenhaus, 2008). In these models, items requiring the establishment of a dependency with another element in the sentence (e.g., filler-gap dependencies or long-distance agreement) can trigger retrieval processes that search working memory for an available, appropriate item with which to establish the dependency. That is, the item triggering the retrieval (the retrieval probe) seeks out another linguistic constituent (the retrieval target) with which to establish a semantic or syntactic relationship, based on a set of cues contained on the retrieval probe. However, when more than one item held in memory resonates with one or more of the retrieval cues, both items may compete as retrieval targets. Thus, an important aspect of cue-based memory retrieval processes is that they are subject to similarity-based interference. This interference can then lead to processing difficulty, which has been reliably indexed by modulations of reading speed (Fedorenko, Gibson, & Rohde, 2006; Gordon, Hendrick, & Johnson, 2001; Gordon, Hendrick, Johnson, & Lee, 2006; Gordon, Hendrick, & Levine, 2002; Gordon & Lowder, 2012; Van Dyke, 2007; Van Dyke et al., 2014; Van Dyke & McElree, 2006).

Similarity-based interference arising during memory retrieval is often invoked to explain a well-studied phenomenon in sentence comprehension known as agreement attraction. Agreement attraction is a phenomenon where language users can become temporarily "confused" about the proper controller of a morphosyntactic subject-verb agreement relationship. This can occur when more than one noun phrase (NP) is available in memory and is therefore a candidate for agreement-dependency formation with a verb. For example, in the ungrammatical sentence "The winner of the trophy were . . .," the verb *were* does not agree in number with the singular feature of the subject NP *the winner* (the "head" noun). In comprehension, ungrammaticalities like this typically lead to processing difficulty, as evidenced by slower reading times and more regressive eye movements in reading studies, and large P600 effects in ERP studies. When encountering an ungrammatical verb like this, cue-based retrieval processes may be initiated, but because there is no candidate plural noun held in memory, no viable agreement dependency can be established. This leads to strong ungrammaticality effects in such sentences. However, in ungrammatical sentences such as "The winner of the trophies were . . .," the plural feature of *were* matches with the plural features of the NP *the trophies* (the "attractor" noun). This can lead the cue-based retrieval process triggered by the probe-verb *were* to mistakenly target *trophies* as the controller of agreement (whereas the correct controller is the singular *winner*).

Retrieving *trophies* instead of *winner* is an example of misretrieval due to agreement attraction and arises because of the plural feature agreement between *trophies* and *were*. Behavioral studies have shown that such cases of agreement attraction substantially reduce the costs of processing ungrammatical verbs, indexed by fewer regressive eye movements and a less pronounced slowdown in reading compared to ungrammatical sentences with no plural attractor (Pearlmutter, Garnsey, & Bock, 1999; Tucker, Idrissi, & Almeida, 2015; Wagers, Lau, & Phillips, 2009). Ungrammaticalities in attraction contexts with a plural attractor thus are perceived to be "less ungrammatical" due to cue-based retrieval interference.

Attraction does not manifest robustly in grammatical sentences, however. That is, recent studies note that there are no clear processing difficulties in grammatical sentences with singular heads and plural attractors (e.g., "The winner of the trophies was . . .") compared to singular-singular head-attractor configurations. This finding has led some to postulate that establishment of subject-verb agreement dependencies utilizes a combination of prediction and retrieval mechanisms (Dillon, Mishler, Sloggett, & Phillips, 2013; Lago, Shalom, Sigman, Lau, & Phillips, 2015; Parker & Phillips, 2016; Tanner, Nicol, & Brehm, 2014; Wagers et al., 2009; see also Mehravari et al., 2015; Tanner & Bulkes, 2015). On this account, morphosyntactic agreement features for the verb are predicted upon encountering the head NP. If a subsequently encountered verb matches with these features, no retrievals must be carried out, so that attraction does not take place. However, if a bottom-up detected verb does not match with predicted features, reanalysis is carried out to reconcile the conflict between the expected and detected features in the input, and memory retrieval is executed to

1. It is worth noting that the functional interpretation of the P600 is still undergoing refinement. We use the term *reanalysis* as a general term, rather than as a description of purely linguistic or syntactic reanalysis. In this way, our terminology is still consistent with proposals holding that the P600 reflects domain-general processing mechanisms like the P300 component (e.g., Bornkessel-Schlesewsky & Schlesewsky, 2008; Coulson, King, & Kutas, 1998; Paczynski & Kuperberg, 2012; van de Meerendonk et al., 2010). The goal of this paper is not, however, to clarify whether the P600 is a member of the broader P300 family (see, e.g., Coulson et al., 1998; Frisch, Kotz, Von Cramon, & Friederici, 2003; Osterhout et al., 1996; Sassenhagen, Schlesewsky, & Bornkessel-Schlesewsky, 2014, for arguments and discussion).

identify whether there is a possible appropriate agreement controller in the sentence representation. At this point, the retrieval mechanism is susceptible to attraction from other nouns held in memory, where misretrievals may occur on a trial-by-trial basis (Lago et al., 2015). The question we ask here is whether this retrieval interference and the reanalysis processes indexed by the P600 in response to prediction errors are independent processes, or whether they are cognitively linked.

In a recent ERP study, Tanner et al. (2014; see also Kaan, 2002) showed that the P600 component elicited by ungrammatical verbs was significantly reduced in cases of agreement attraction (i.e., when a singular head and plural attractor noun precede a plural verb: henceforth "attraction sentences") compared to sentences where both the head and attractor nouns were singular and co-occurred with a plural verb ("no-attraction sentences"). This P600 reduction was found in the absence of any unique effect of attractor number at the verb, indicating that P600 reduction is a reliable marker of attraction interference. That is, processing costs associated with ungrammatical plural verbs were ameliorated following plural attractors, but plural attractors did not make grammatical verbs more difficult to process. However, it is unclear whether this retrieval interference in ungrammatical sentences is part of the reanalysis processes indexed by the P600 (i.e., whether P600 reduction is a direct reflection of the establishment of the erroneous agreement dependency), or whether P600-related reanalysis is a process independent of and downstream from memory retrieval interference (i.e., whether P600 reduction reflects a decreased engagement of general reanalysis processes following a misretrieval).

This issue is aligned with a related question as to whether the onset of the P600 can be taken as a primary index of the timing of anomaly detection, as some have suggested (e.g., Allen et al., 2003; McKinnon & Osterhout, 1996), or whether the P600 reflects processes triggered by, but downstream from, anomaly detection (e.g., Friederici, 2002; Molinaro, Barber, & Carreiras, 2011). If the P600 is a primary index of anomaly detection, then we would expect that retrieval and P600-related reanalysis are interconnected. If the P600 reflects processes downstream from initial anomaly detection, however, we would expect to find evidence that the two sets of processes are at least somewhat independent. The present study sought to disentangle these issues.

Currently, there is some behavioral evidence pointing to both alternatives. For example, recent eye tracking evidence (Dillon et al., 2013) shows that ungrammaticality effects in attraction sentences were present during first-pass reading measures, but attraction interference effects did not appear until a very late measure of processing: total reading time. This suggests that cue-based memory retrieval interference does not impact the earliest stages of processing ungrammatical subject-verb agreement dependencies. Instead, evidence for attraction is found only in late measures of processing, which are usually argued to index reprocessing and reanalysis (e.g., Staub & Rayner, 2007). Based on this evidence, one might conclude that both reanalysis and retrieval interference are late processes, initiated after an ungrammatical verb is detected. In terms of the P600, this is consistent with the proposal that memory retrieval, and therefore retrieval interference, could be part of the general reanalysis processes indexed by the late positivity. In this scenario, retrieval and reanalysis could be dependent and cognitively linked processes. As such, P600 reductions may directly reflect (at least partially) these memory misretrievals.

Conversely, Van Dyke and Lewis (2003) provide evidence that retrieval interference and reanalysis may be at least partially independent. Their evidence is largely from offline grammaticality judgments of garden path sentences (e.g., "The frightened boy understood (that) the man was paranoid about dying," where *the man* is temporarily ambiguous between being the object of *understood* or the subject of a new clause when *that* is absent). They showed that acceptability ratings of sentences decreased both when there was a temporary syntactic ambiguity (i.e., a garden path effect when the word *that* was absent) and when there was a high load of syntactic interference from an embedded object relative clause, regardless of whether or not the sentence was temporarily ambiguous. That is, the reanalysis and interference effects on sentence acceptability were largely independent. Although their study employed mainly offline judgments and used garden path sentences (unlike the agreement attraction sentences above), the findings of Van Dyke and Lewis suggest that retrieval interference effects can be found in the absence of any sort of sentence-level reanalysis. This indicates some independence of reanalysis and retrieval, though the extent to which these findings generalize to online sentence comprehension and electrophysiological components of language comprehension like the P600 is not clear.

The goal of the present study was to provide a clearer test of the relationship between cue-based memory retrieval and the reanalysis processes reflected in the P600 during sentence comprehension. In particular, this study tested two contrastive accounts of P600 reductions in agreement attraction contexts: whether P600 reductions in memory-interference contexts might directly reflect misretrievals, which would indicate that retrieval interference could be one of the reanalysis processes reflected in the P600, or, alternatively, whether P600 reductions reflect reduced reanalysis as a consequence of a misretrieval having already taken place (i.e., whether the P600 reflects reanalysis processes that are independent of memory retrieval interference). To test this, we combined a sentence processing paradigm containing agreement attraction sentences like those studied by Tanner and colleagues (2014) with a timing manipulation designed to modulate participants' ability to engage in reanalysis processes. This timing manipulation modulated word presentation rate in a rapid serial visual presentation (RSVP) paradigm. Sentences were presented at either a slow rate (650 ms per word), medium rate (450 ms per word, which is a fairly typical rate in sentence processing studies), or fast rate (233 ms per word, which is much faster than used in most sentence processing studies; cf. Hagoort & Brown, 2000).

First, we hypothesized that agreement attraction contexts would lead to reduced P600 effects, relative to no-attraction contexts; this should manifest as an interaction between grammaticality and attractor number (Tanner et al., 2014). Second, we hypothesized that fast presentation of words would lead to decreased engagement of reanalysis processes (i.e., reduced P600 amplitudes; see, e.g., Otten & Rugg, 2005; Rugg & Coles, 1995). This hypothesis stems from prior ERP work on language and other cognitive domains. First, fast stimulus-onset asynchronies (SOAs) have been shown to reduce prediction during sentence comprehension (Wlotko & Federmeier, 2015), and prediction of morphosyntactic features has been argued to be a key facet of agreement comprehension (Dillon et al., 2013; Tanner et al., 2014; Wagers et al., 2009). Reducing participants' capacity to anticipate agreement features should thus reduce ungrammaticality effects. Second, fast presentation would require more attention to the incoming stimuli just to comprehend the sentence at a basic level, thereby leaving fewer cognitive resources available to engage in reanalysis processes. Work within the linguistic domain has shown that the amplitude and onset of the P600 is modulated by memory load (Kolk, Chwilla, van Herten, & Oor, 2003; Vos, Gunter, Kolk, & Mulder, 2001), which indicates

Table 1. *Example Sentences from the Experiment*

Grammaticality	Attraction	Example sentence
Grammatical	No attraction	The slogan on the political poster was shouted by the demonstrators.
Ungrammatical	No attraction	The slogan on the political poster were shouted by the demonstrators.
Grammatical	Attraction	The slogan on the political posters was shouted by the demonstrators.
Ungrammatical	Attraction	The slogan on the political posters were shouted by the demonstrators.

Note. The critical word for ERP time-locking and averaging is underlined.

that drawing cognitive resources away from reanalysis processes reduces the P600. Moreover, individual differences in cognitive capacity can modulate P600 amplitudes, with smaller amplitudes found in individuals with smaller processing capacities (Nakano, Saron, & Swaab, 2010; Oines, Miyake, & Kim, 2012). Analogously, work on processing capacity and the P300 has found reduced P300 amplitudes in situations where the cognitive demand on participants is high (Watter, Geffen, & Geffen, 2001; see also Polich, 2012). Importantly, research also demonstrates that shorter SOAs lead to reduced P300 amplitudes (Fitzgerald & Picton, 1981; Gonsalvez & Polich, 2002; Woods & Courchesne, 1986). In these cases, P300 reductions are interpreted as reflecting decreases in the availability of cognitive resources for maintaining and updating stimulus properties in memory with faster SOAs. We therefore expected our SOA manipulation to also have an effect on the P600 during sentence comprehension.

The key question was whether the manipulations of SOA and agreement attraction would interact. If they do interact, this would suggest that cue-based retrieval processes are nonindependent of the reanalysis processes indexed by the P600. That is, reducing participants' ability to engage in reanalysis processes should impact their ability to engage in cue-based retrieval processes, such that reduced P600s associated with faster SOAs should co-occur with reductions in attraction effects on the P600. Alternately, finding independent and additive effects of SOA and attraction on the P600 would suggest that retrieval and sentence-level reanalysis are to a certain extent independent and separable processes.

Method

Participants

Our participants were 132 functionally monolingual native speakers of English. All participants were right-handed (Oldfield, 1971), had normal or corrected-to-normal vision, and reported no history of neurological impairments. Data from 13 participants were excluded due to either excessive artifacts in the raw EEG or technical difficulties during recording. This left 119 participants in the final analysis: 42 in the fast SOA group (10 male; mean age 19.2 years, range: 18–26), 40 in the medium SOA group (12 male; mean age 19.4 years, range: 18–35), and 37 in the slow SOA group (11 male, mean age 19.3 years, range: 18–26). All participants received course credit for taking part in the study.

Materials

Materials were 120 sentences created in a 2 (Grammaticality) × 2 (Attraction) design. All sentences had subject NPs with an embedded prepositional phrase. All subject NPs had singular head nouns; attraction was manipulated by varying the number feature of the noun embedded in the prepositional phrase as singular (no attraction) or plural (attraction). Grammaticality was manipulated based on whether or not the verb in the sentence agreed in number with the head noun; grammatical sentences had proper singular agreement, whereas ungrammatical sentences had plural agreement.[2] The choice to use only singular head nouns was made based on prior work on agreement attraction, which shows that singular attractors following plural head nouns exert significantly less interference than plural attractors following singular heads because of markedness differences between singulars and plurals (Bock & Miller, 1991; Eberhard, Cutting, & Bock, 2005; Eberhard, 1997; Pearlmutter et al., 1999; Staub, 2009). Additionally, as prior work on attraction in both comprehension and production has used auxiliary verbs as the critical agreeing verb (*is/are, was/were*), we did the same (Brehm & Bock, 2013; Dillon et al., 2013; Nicol, Forster, & Veres, 1997; Pearlmutter et al., 1999; Tanner et al., 2014; Wagers et al., 2009). See Table 1 for an example. Sentences were distributed across four lists in a Latin square design, such that each list had 30 items from each condition, and no list contained two versions of the same item. One hundred and twenty filler sentences included sentences with semantic expectancy violations and sentences with omitted tense morphemes (see Tanner & van Hell, 2014). Each list thus contained 240 sentences, half of which contained either a morphosyntactic or semantic anomaly.

Procedure

Participants were tested in a single session lasting approximately 2.5 h. Following informed consent, each participant completed a language background questionnaire and an abridged version of the Edinburgh Handedness Inventory (Oldfield, 1971). Participants were then seated in a comfortable chair in a sound-attenuating chamber and completed a sentence acceptability judgment task while EEG was recorded.

Each trial began with a blank screen for 500 ms followed by a fixation cross, followed by a sentence presented one word at a time in RSVP format. For all SOA conditions, the interstimulus interval was 100 ms. For the fast SOA condition, the fixation cross and words were presented for 133 ms (each followed by a 100-ms blank screen); for the medium SOA condition, the fixation cross and words were each presented for 350 ms (followed by a 100-ms blank screen); for the fast SOA condition, the fixation cross and words were each presented for 550 ms (followed by a 100-ms blank screen). Sentence-final words appeared with a full stop. After each sentence, a "Good/Bad?" prompt appeared on the screen, and participants indicated with a button press whether they felt the sentence was grammatical and semantically well formed (good) or ungrammatical or nonsensical (bad). The response hand (left/right) for the good response was counterbalanced across participants. During the task, participants were encouraged to relax and read each sentence as naturally as possible, while minimizing eye movements and blinks. Between trials, a screen with the word "Ready?"

2. Data from the medium SOA group in the no-attraction condition were reported in Tanner and van Hell (2014).

Table 2. *Accuracy from the Behavioral Acceptability Judgment Task*

	No attraction		Attraction			
Group	Grammatical proportion correct	Ungrammatical proportion correct	Grammatical proportion correct	Ungrammatical proportion correct	No attraction A′	Attraction A′
Fast SOA	.920 (.013)	.806 (.033)	.878 (.014)	.615 (.038)	.916 (.010)	.827 (.015)
Medium SOA	.955 (.007)	.915 (.015)	.910 (.012)	.748 (.028)	.965 (.010)	.897 (.015)
Slow SOA	.942 (.008)	.904 (.022)	.897 (.013)	.781 (.032)	.957 (.010)	.900 (.015)

Note. Standard errors are reported in parentheses.

appeared, during which participants could blink or rest their eyes. Participants began the subsequent trial with a button press. Following this task, participants also completed a battery of memory and language measures that are not discussed here (see Tanner & van Hell, 2014).

EEG Data Acquisition and Analysis

Scalp EEG was recorded from 32 active scalp electrodes mounted in an elastic cap (Brain Products ActiCap, Germany) from an extended 10-20 montage. EEG was amplified using a Neuroscan Synamps RT system, and filtered online with a 0.05–100 Hz bandpass and recorded with a 500 Hz sampling rate. Offline data analysis used EEGLAB (Delorme & Makeig, 2004) and ERPLAB (Lopez-Calderon & Luck, 2014) toolboxes for MATLAB. Data were filtered offline with a 30 Hz half-amplitude low-pass filter (24 dB/octave roll-off). Scalp electrodes were referenced online to either the right mastoid or a vertex electrode, and rereferenced offline to the average of the activity over the left and right mastoids. Additional electrodes were placed above and below the left eye and at the outer canthus of each eye, both referenced in bipolar montages, in order to screen for ocular artifacts. Impedances at all sites were kept below 10 kΩ. For three participants in the slow SOA group, electrode C4 was faulty. This electrode was interpolated offline using a spherical spline interpolation with EEGLAB's *pop_interp* function in these participants only.

ERPs, time-locked to the critical verbs (underlined in Table 1), were averaged offline for each condition at each electrode for each participant, relative to a 200-ms prestimulus baseline. All artifact-free trials were included in the analyses. Artifact rejection rates were 6.7%, 4.4%, and 8.0% for the fast, medium, and slow SOA conditions, respectively. Our primary analysis focused on the 500–800 ms poststimulus time window, which corresponds to the P600 effect (e.g., Tanner et al., 2014). We additionally analyzed the 300–500 ms poststimulus window, as some reports have shown either N400 or left anterior negativity effects to morphosyntactic violations during that time window (e.g., Molinaro et al., 2011).

P600 effects are maximal over midline scalp sites, and we therefore focused our analyses on data collected from midline electrodes (Fz, Cz, Pz, Oz) for three main reasons: for brevity, to reduce the number of analyses and potential for Type I error in the analysis of variance (ANOVA) outcomes (see Luck & Gaspelin, in press, for discussion), and because prior work showing that analysis of midline sites adequately characterizes P600 effects in morphosyntactic violation contexts like those employed in the current study (Allen et al., 2003; Tanner et al., 2014). Data from these four electrodes were submitted to a mixed ANOVA with grammaticality, attraction, and electrode as repeated measures factors and SOA as a between-subjects factor. All repeated measures contrasts with more than one degree of freedom in the numerator used the Greenhouse-Geisser correction for inhomogeneity of variance; in such cases, the corrected *p* value but uncorrected degrees of freedom are reported. Analyses from lateral electrode sites are available in the supporting online information.

Results

Behavioral Results

Results from the acceptability judgment task were quantified using A′ scores (Stanislaw & Todorov, 1999), a nonparametric signal detection statistic, and are presented in Table 2. An ANOVA on A′ scores showed main effects of attraction, $F(1,116) = 153.483$, $MSE = 0.002$, $p < .001$, $\eta^2_p = .569$, and SOA, $F(2,116) = 8.583$, $MSE = 0.011$, $p < .001$, $\eta^2_p = .129$, but no reliable interaction between the two factors, $F(2,116) = 2.664$, $p = .07$. Bonferroni post hoc tests for the effect of SOA showed significant differences between the fast and medium SOA groups ($p = .001$, Cohen's $d = 0.82$) and the fast and slow SOA groups ($p = .002$, Cohen's $d = 0.79$), but no difference between the medium and slow groups ($p = 1.000$). Overall, this shows a reliable attraction effect, demonstrating a reduction in behavioral sensitivity to ungrammaticality in sentences containing plural attractors in all three SOA conditions. Moreover, at the fastest SOA condition, sensitivity was lower than at the medium and slow SOAs, suggesting that fast SOAs indeed increased cognitive demand during sentence comprehension. Note, however, that A′ scores in all SOA conditions and in both the attraction and no-attraction conditions were high and far above chance, indicating that participants could still reliably read and attend to the sentences for purposes of the acceptability judgment task, even in the fast SOA condition.

Electrophysiological Results

Grand mean ERP waveforms from the fast, medium, and slow SOA conditions are presented in Figure 1, 2, and 3, respectively. Visual inspection showed that ungrammatical verbs elicited a late posterior positivity, relative to grammatical verbs. Notably, the size of the positivity was not only smaller in attraction contexts (an agreement attraction effect), but also reduced in amplitude with faster SOAs. These attraction and SOA effects are shown in Figure 4, which depicts ungrammatical minus grammatical difference waves for each attraction and SOA condition over five centroparietal electrodes, where P600 effects are typically largest.

In the 500–800 ms time window,[3] there was a main effect of grammaticality, $F(1,116) = 116.932$, $MSE = 17.717$, $p < .001$,

3. Inspection of waveforms in the 300–500 ms time window showed a small negativity in the ungrammatical relative to grammatical sentences for all three SOA conditions; statistical analysis revealed that this effect was not reliable ($p > .05$). There was also no attraction effect or an interaction between attraction and grammaticality. Additionally, SOA did not interact with either of these factors.

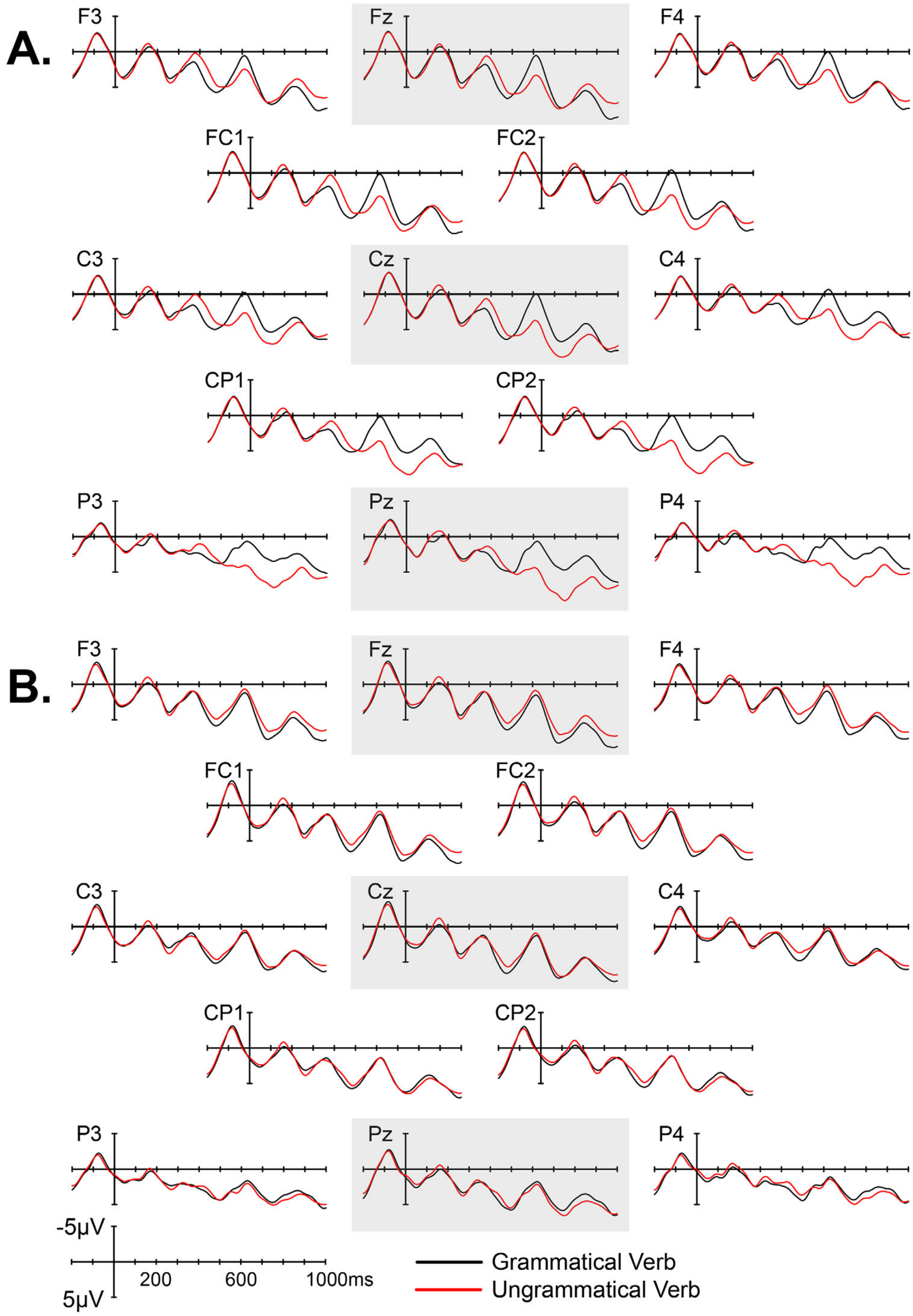

Figure 1. Grand mean ERPs over 13 representative electrodes in the fast SOA condition ($n = 42$) for the no-attraction (A) and attraction (B) conditions. Waveforms depict 200 ms of prestimulus and 1,000 ms of poststimulus activity. Brain responses to grammatical verbs are plotted in black, and brain responses to ungrammatical verbs are plotted in red. The vertical calibration bar indicates the onset of the critical verb and depicts 5 μV of activity; negative voltage is plotted up. These and all subsequent waveforms were filtered with a 15 Hz low-pass filter for plotting purposes only. Midline electrodes used in the primary analyses are highlighted in gray.

$\eta_p^2 = .502$, which showed a posterior distribution (grammaticality by electrode interaction: $F(3,348) = 45.216$, $MSE = 3.851$, $p < .001$, $\eta_p^2 = .280$). There was also an attraction effect, as indicated by a significant interaction between grammaticality and attraction, $F(1,116) = 74.376$, $MSE = 12.133$, $p < .001$, $\eta_p^2 = .391$. The attraction effect also showed a largely posterior focus (Grammaticality × Attraction × Electrode interaction: $F(3,348) = 8.108$, $MSE = 2.479$, $p = .001$, $\eta_p^2 = .065$. This attraction effect demonstrates that P600 amplitudes were reliably smaller when ungrammatical verbs followed a plural attractor than when they followed a singular attractor (cf. Tanner et al., 2014), and that this effect had a typical posterior distribution. Figure 5 depicts the scalp topographies of the ungrammatical minus grammatical difference waves for each attraction and SOA condition between 500 and 800 ms

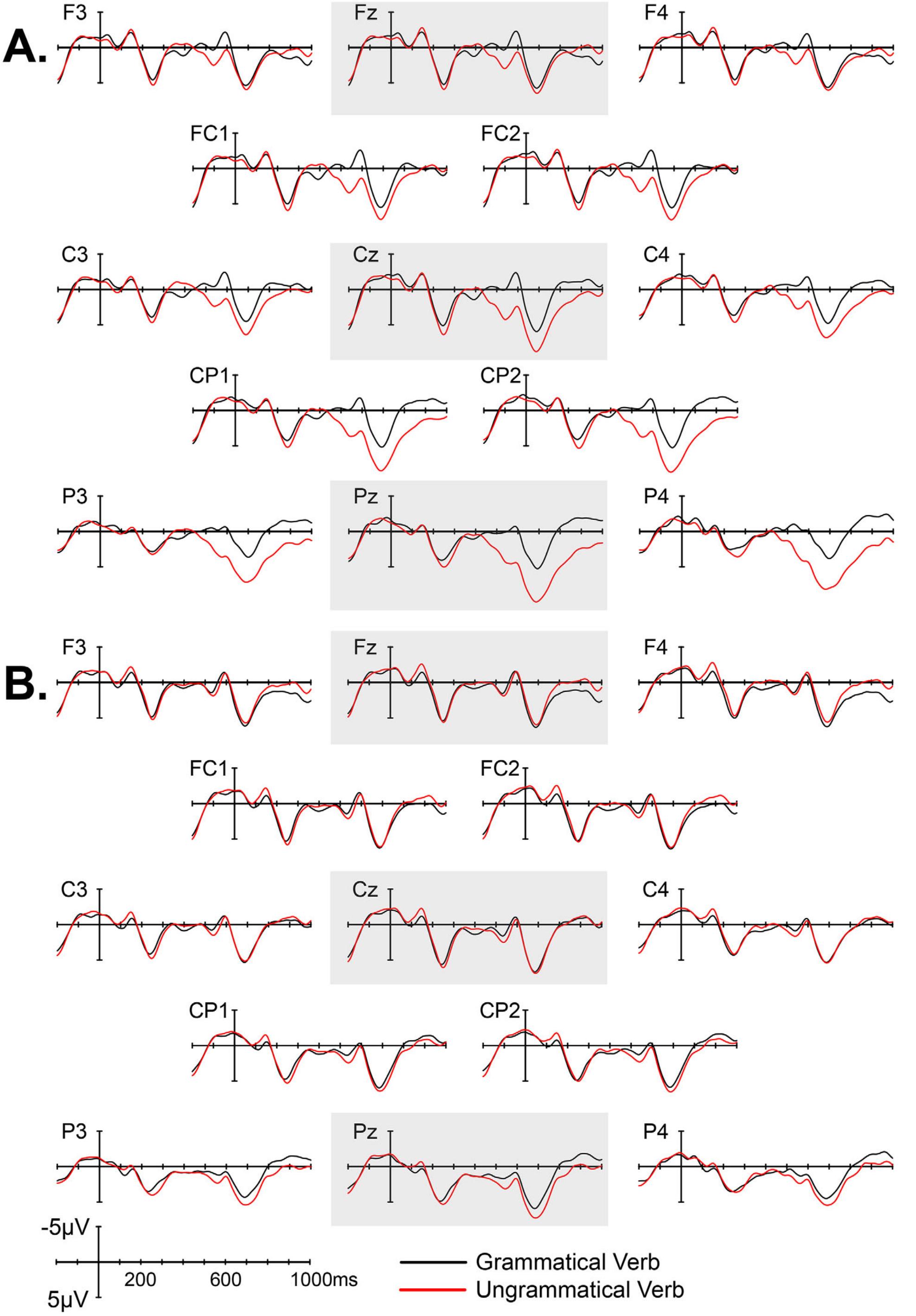

Figure 2. Grand mean ERPs in the medium SOA condition ($n = 40$) for the no-attraction (A) and attraction (B) conditions.

poststimulus. As can be seen, the P600 effects had largely similar scalp topographies across all conditions, suggesting they reflect the same basic underlying process, regardless of SOA or attraction.

Importantly, there was also an interaction between grammaticality and SOA, $F(2,116) = 7.456$, $MSE = 17.717$, $p < .001$, $\eta_p^2 = .114$, showing that P600 effects were smaller in the faster SOA groups than the slower SOA groups, and that this effect was approximately linear. Also of importance is that there was not even a trend toward a further interaction between grammaticality, attraction, and SOA ($F = .264$, $p = .769$), even with a large sample size of $N = 119$. This indicates that the attraction effect was not modulated in any way by the SOA manipulation. This lack of interaction suggests that the effects of SOA and attraction on P600 amplitude are largely additive and independent, allowing for the inference that retrieval interference underlying attraction is not part of the reanalysis processes indexed by the P600.

Discussion

This study investigated factors related to the P600 ERP component elicited during sentence comprehension. We asked whether the

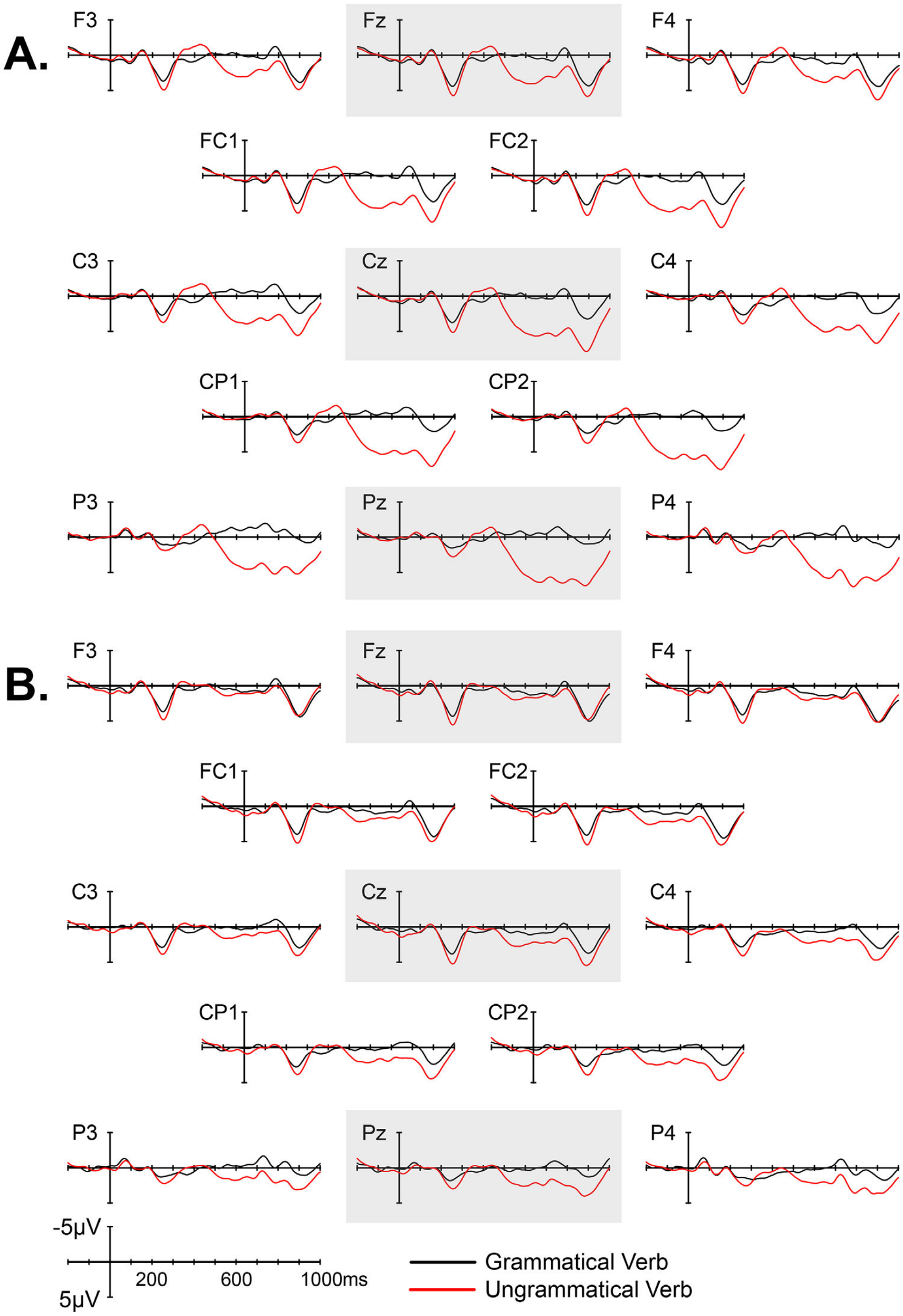

Figure 3. Grand mean ERPs in the slow SOA condition ($n = 37$) for the no-attraction (A) and attraction (B) conditions.

reanalysis processes indexed by the P600 directly index cue-based memory retrieval processes involved in the establishment of long-distance dependencies, or whether these cue-based retrieval and reanalysis processes are largely independent. We manipulated factors related to retrieval interference (agreement attraction) and also factors that we predicted would modulate participants' ability to engage in reanalysis processes (SOA). First, ungrammaticalities elicited classic P600 effects, which were reduced in agreement attraction contexts (the agreement attraction effect). Second, faster SOAs decreased P600 amplitude relative to slower RSVP rates, consistent with the hypothesis that faster presentation rates decrease participants' engagement of reanalysis processes. Most importantly for our purposes, this SOA effect was fully independent of the agreement attraction effect we observed, as no interaction between grammaticality, attraction interference, and SOA was observed. The very large sample size in our study ($N = 119$) and the lack of even a trend toward an interaction strongly suggest that the SOA and attraction effects are largely additive, and that

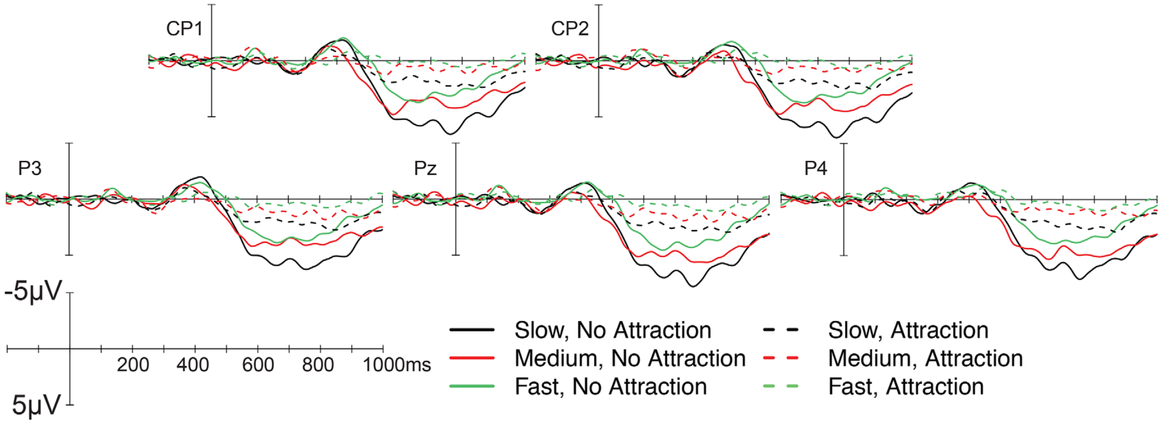

Figure 4. Difference waves (ungrammatical minus grammatical) over five centroparietal electrode sites showing the effects of SOA and attraction on P600 amplitude.

retrieval interference and the reanalysis processes indexed by the P600 are to a certain extent neurocognitively independent.[4]

From this independence, one inference is that the attraction-related P600 reduction we observed does not directly reflect retrieval interference, since the magnitude of the attraction effect was not modulated by the SOA manipulation. If the two were interdependent, we should have observed a concomitant reduction in both the effects of attraction and grammaticality on the P600. Instead, our findings suggest a processing architecture where the P600 reflects processes independent of and downstream from the cue-based retrieval interference giving rise to attraction effects. In conjunction with prior eye tracking work (Dillon et al., 2013; Parker & Phillips, 2016), our data suggest a temporal ordering of processes related to morphosyntax, where anomaly detection precedes memory retrieval processes, which precedes reanalysis as reflected in the P600. This is consistent with proposals arguing that initial ungrammaticality detection can be made on the basis of feature predictions, at least for frequent obligatory morphosyntactic dependencies such as English agreement, but that attraction follows misretrieval of the number-matching attractor noun (Dillon et al., 2013; Lago et al., 2015; Parker & Phillips, 2016; Tanner et al., 2014; Wagers et al., 2009). Our findings therefore place an important constraint on the interpretation of the P600, namely, that the P600 only indirectly reflects detection of morphosyntactic anomalies, and specifically reanalysis (cf. Hahne & Friederici, 1999; Molinaro et al., 2011). This also contrasts with some proposals that the onset of the P600 can be taken as a primary index of the detection of syntactic anomalies (e.g., Allen et al., 2003; McKinnon & Osterhout, 1996).

Our findings also extend the offline behavioral evidence presented by Van Dyke and Lewis (2003) in important ways. They found that decreases in acceptability judgment accuracy were found for garden path sentences with and without retrieval interference, but, importantly, that when sentences were unambiguous (i.e., contained no garden path), retrieval interference did show a negative impact on acceptability judgments (while syntactic complexity did not). Based on those results, Van Dyke and Lewis concluded that reanalysis and retrieval interference are likely cognitively separable. Our results extend their findings into the neurocognitive domain to show that memory retrieval and reanalysis may indeed be independent processes in sentence comprehension. It additionally extends the finding to cases of core morphosyntax, with an obligatory grammatical feature of English (subject-verb agreement), and not just with infrequent and highly difficult-to-process garden path sentences. Finding this dissociation in two linguistic domains (garden path complexity and core morphosyntax) and with two research paradigms (behavioral and neurocognitive) provides corroborating evidence for the general independence of cue-based memory retrieval processes and sentence-level reanalysis.

Finally, our study is the first to directly investigate SOA effects on the P600 elicited during morphosyntactic processing that we are aware of, and the first to show that when other factors are held constant, faster SOAs lead to reduced P600 amplitudes. Others have investigated P600 effects with fast SOAs, but made no direct comparison to data elicited under slower SOA conditions (e.g., Hagoort & Brown, 2000). We hypothesize that the reduced P600 amplitude we observed reflects decreased engagement of cognitive processes associated with reanalysis. In the introduction, we noted that faster rates of presentation may tax the language processing system in two ways. First, fast speeds may decrease participants' ability to predict upcoming features, leading to decreased engagement of reanalysis processes; second, more attention must be spent on processing the input leaving fewer cognitive resources for reanalysis.[5] Documenting the effect of SOA on P600 amplitude makes an important methodological contribution for future work focusing on the P600, where timing factors may impact relative effect size and statistical power. Moreover, it should provide a cautionary note for those conducting meta-analyses and reviews of P600 effects across

4. Note that some caution is needed here, as this involves interpreting a null three-way interaction. However, we also point out that all of the effects we expected a priori were significant. These include the overall effect of grammaticality (showing a reliable P600 effect), the interaction between grammaticality and attraction (indexing a reliable attraction effect), and the interaction grammaticality and SOA (indexing the reduction of the P600 effect associated with greater processing pressure at fast SOAs). Thus, our design was sufficiently sensitive, and we had enough statistical power to detect all of our expected effects.

5. Lago and colleagues (2015) used response time distributional data to suggest that attraction effects in reading time are a result of misretrievals impacting only some trials, with the net impact after averaging being a reduced ungrammaticality effect. This type of trial-by-trial variation could also be responsible for the P600 reduction seen in attraction sentences here. It remains an area for future research whether the P600 reduction associated with SOA reflects reduced engagement of these processes/reduced P600 amplitude on every trial, or whether there are similar trial-by-trial differences in amplitude, with the net effect averaging being an overall reduction in amplitude.

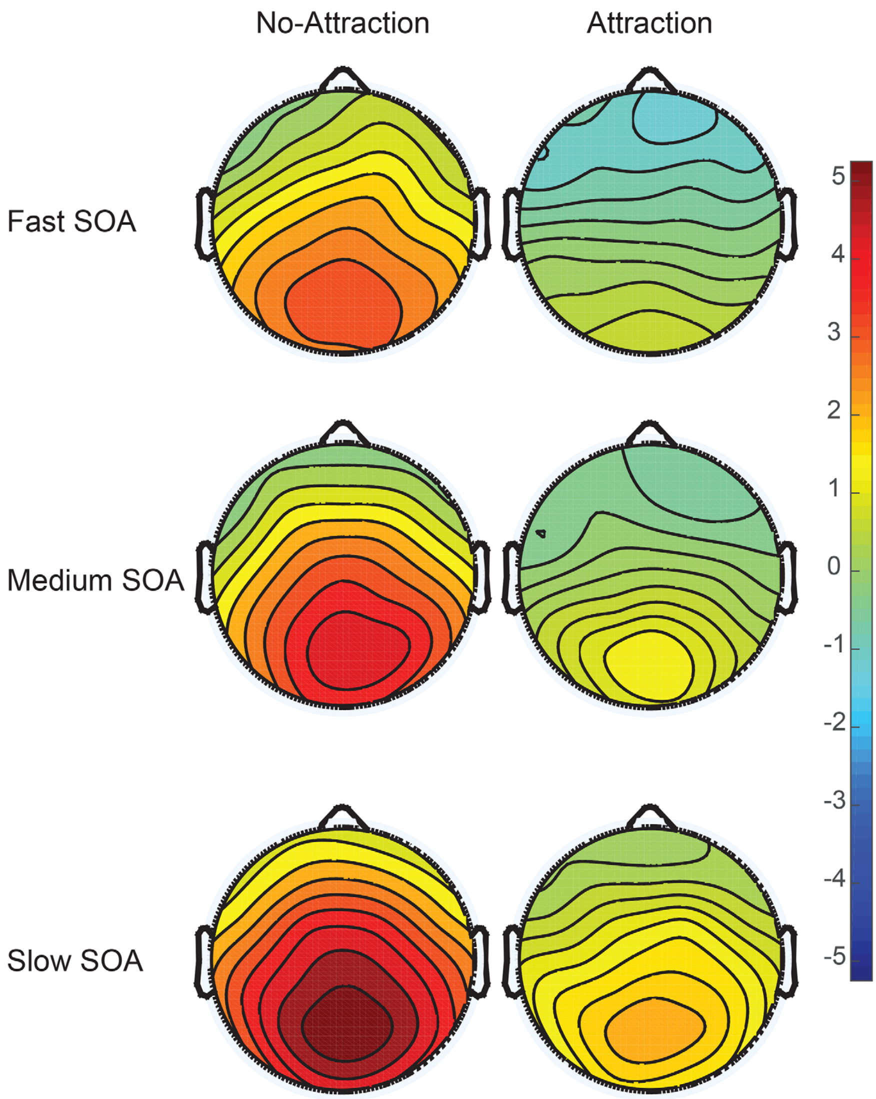

Figure 5. Topographic maps depicting the distribution of the P600 effects for each of the attraction and SOA conditions, computed from the ungrammatical minus grammatical difference waves between 500 and 800 ms poststimulus. Calibration scale is in microvolts.

studies, such that SOA needs to be taken into consideration when measuring effect amplitudes.

Conclusion

We investigated the relative independence of late reanalysis processes in sentence comprehension, indexed by the P600 ERP component, and the memory retrieval systems which support formation of long-distance linguistic dependencies. Consistent with prior work, we found that morphosyntactic subject-verb agreement dependencies were subject to similarity-based retrieval interference in the form of attraction effects that reduced the amplitude of the P600 to ungrammatical verbs. We further found that faster SOAs with RSVP stimulus presentation also reduced P600 effects, consistent with a reduction in engagement of reanalysis processes under processing pressure. Importantly, the attraction- and SOA-based P600 reductions showed no evidence of an interaction, suggesting that cue-based memory retrieval interference and late reanalysis processes are independent of one another. Our data further suggest that the P600 effect reflects processes engaged after the initial detection of a morphosyntactic anomaly, and is not a primary index of anomaly detection itself.

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Supporting Information

Additional supporting information may be found in the online version of this article:

Table S1: ANOVA results from lateral electrode sites in the 500–800 ms time window.

Table S2: Step-down ANOVAs over each hemisphere in the 500–800 ms time window.