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Neural measures reveal implicit learning during language processing

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Abstract

Language input is highly variable; phonological, lexical and syntactic features vary systematically across different speakers, geographic regions, and social contexts. Previous evidence shows that language users are sensitive to these contextual changes and that they can rapidly adapt to local regularities. For example, listeners quickly adjust to accented speech, facilitating comprehension. It has been proposed that this type of adaptation is a form of implicit learning. The present study examined a similar type of adaptation, syntactic adaptation, in order to address two issues: (1) whether language comprehenders are sensitive to a subtle probabilistic contingency between an extraneous feature (font color) and syntactic structure, and (2) whether this sensitivity should be attributed to implicit learning. Participants read a large set of sentences, 40% of which were garden-path sentences containing temporary syntactic ambiguities. Critically, but unbeknownst to participants, font color probabilistically predicted the presence of a garden-path structure, with 75% of garden-path sentences (and 25% of normative sentences) appearing in a given font color. Event-related brain potentials (ERPs) were recorded during sentence processing. Almost all participants indicated no conscious awareness of the relationship between font color and sentence structure. Nonetheless, after sufficient time to learn this relationship, ERPs time-locked to the point of syntactic-ambiguity resolution in garden-path sentences differed significantly as a function of font color. End-of-sentence grammaticality judgments were also influenced by font color, suggesting that a match between font color and sentence structure increased processing fluency. Overall, these findings indicate that participants can implicitly detect subtle co-occurrences between physical features of sentences and abstract, syntactic properties, supporting the notion that implicit learning mechanisms are generally operative during online language processing.

Introduction

Language input is highly variable, given that different speakers exhibit different pronunciations, inflectional patterns, syntactic preferences, and word choices. Despite this variability, we are typically able to comprehend language with little effort, even when the input is very different from the norm. For example, learners are able to readily comprehend nonnative, accented speech by adjusting their reliance on particular acoustic dimensions during word recognition (Idemaru & Holt, 2011). This type of online adjustment allows language users to accommodate acoustic variability arising from individual, accent, and dialect differences, and has been shown to occur very rapidly, emerging after only 10 exposure trials (Idemaru & Holt, 2011). This example illustrates that language comprehension requires sensitivity not only to long-term regularities of a speaker's native language, shaped gradually through cumulative experience over protracted time periods, but also to short-term, local regularities, shaped rapidly through recent experience.

This type of rapid adjustment has also been observed in the domain of syntax. Syntactic priming—a facilitation in processing of sentences that share a common structure—is a well-known example. Syntactic priming has been most commonly studied in the domain of production (e.g., Bock, 1986; cf. Ledoux et al., 2007), in which it is revealed as a tendency for speakers to repeat recently encountered syntactic structures in new utterances. Syntactic priming also occurs in comprehension, and has been demonstrated through anticipatory eye movement (Carminati, van Gompel, Scheepers, & Arai, 2008; Thothathiri & Snedeker, 2008; Traxler, 2008), reading times (Traxler & Tooley, 2008), and picture-matching choices for ambiguous phrases (Branigan et al., 2005).

Syntactic processing is influenced not only by the immediately preceding context (i.e., the prime sentence), but also by cumulative experience, such as that accrued over the course of an experimental session. A prime example is provided by studies of garden-path sentences resolved by relative clauses (e.g., "The experienced soldiers warned about the dangers conducted the midnight raid"). These sentences contain temporary syntactic ambiguities, which can be resolved only after reading subsequent words. Frequent exposure to such sentences over the course of an experimental session eliminates the cost associated with processing these ambiguities, as revealed by reading times (Fine et al., 2013). Conversely, sentences with expected or typical structures become more difficult to process when they are rarely presented among frequent garden-path sentences within an experimental session (Fine et al., 2013). Along the same lines, participants rate sentences with ambiguous or unusual syntactic structures as more grammatically acceptable if they have previously read other sentences that share this syntactic structure (Luka & Barsalou, 2005; Luka & Choi, 2012). It has been proposed that this shift in grammatical preference is similar to the mere exposure effect, in which previously encountered stimuli receive higher ratings of liking (Zajonc, 1968). This grammatical acceptability effect is induced very rapidly, observable after a single prior exposure to the syntactic structure, and persists for at least a full week after initial exposure (Luka & Choi, 2012).

It has been proposed that this syntactic adaptation is a form of *implicit learning* (e.g., Segaert & Hagoort, in press; Fine et al., 2013; Fine & Jaeger, 2013; Bock & Griffin, 2000; Bock et al., 2007; Luka & Barsalou, 2005)—that is, learning that occurs incidentally and that produces knowledge that is inaccessible to awareness (Seger, 1994; Frensch and Rünger, 2003; Reber, 1967; Foerde, 2010; Reber, 2013). This idea is supported by a number of different lines of evidence. For example, the strength of syntactic priming has been shown to be unrelated to participants' explicit memory of the prime sentences' syntactic form, as assessed through a forced-choice recognition memory test (Bock et al., 1992). This finding suggests that syntactic priming effects are dissociable from explicit memory. Another piece of evidence supporting this idea comes from studies of amnesic patients, who show intact syntactic priming despite a marked impairment in recognition memory for the prime sentences (Ferreira et al., 2008). Again, this result points to a dissociation between syntactic priming and explicit memory. Finally, the idea that syntactic priming is a form of implicit learning is also supported computationally. Chang and colleagues (2000, 2006) found that the same connectionist models that can account for implicit sequential learning, in which participants respond quickly to a series of stimuli that follow certain patterns, can be successfully applied to syntactic priming. Similar to signature implicit learning tasks such as sequence learning, syntactic priming also appears to involve incidental learning of complex abstracts relations and to yield knowledge that is inaccessible to awareness (Chang et al., 2000). Collectively, these results provide evidence that syntactic adaptation is driven by implicit learning.

Linguistic adaptation effects can show a high degree of specificity (e.g., Creel et al., 2008; Eisner & McQueen, 2005; Kraljic & Samuel, 2005, 2007; Bradlow & Bent, 2008). During speech recognition, for example, listeners are capable of acquiring and maintaining separate phonemic representations for individual speakers, as revealed by different categorization of phonemic contrasts for different speakers. Interestingly, this speaker-specific adaptation appears to occur only for phonemic contrasts that reliably signal a particular speaker (Kraljic & Samuel, 2005, 2007). Listeners adapt not only to individual speaker's phonetic characteristics, but also to their lexical (Creel et al., 2008; Horton & Slaten, 2012) and syntactic (Kamide, 2012) choices. Using eye-tracking methods during spoken word recognition, Creel and colleagues (2008) showed that listeners use speaker identity to disambiguate competitor lexical items (e.g., *sheep* versus *sheet*). Similarly, Kamide (2012) found that listeners become sensitive to individual speakers' syntactic preferences. When exposed to two different speakers, one who always resolved structurally ambiguous sentences with high attachment and one who resolved them with low attachment, participants learned to anticipate the appropriate resolution of the sentence according to the speaker's identity, as revealed through their eye fixations to a visual display with several competing objects.

The goal of the present study was to provide a further characterization of the learning mechanisms that contribute to these types of adaptation effects, by investigating whether these mechanisms operate when contextual contingencies are highly subtle and whether conscious awareness of the contingencies is required. We built upon Kamide's (2012) intriguing finding that comprehenders can dynamically change their expectations about abstract, structural properties of language on a trial-by-trial basis as a function of speaker identity. As in Kamide's design, we presented syntactic ambiguities that were correlated with contextual, extralinguistic cues. Specifically, learners read garden-path sentences containing temporary syntactic ambiguities, presented in one of two font colors, one word at a time. Unbeknownst to the participants, the font color probabilistically predicted the presence of a garden-path structure, with 75% of garden-path sentences appearing in a given color. We used font color as a model of the background cues—such as speaker voice—that correlate systematically with different features of language. Although font color represents a relatively artificial manipulation compared to voice characteristics, it enabled us to create a highly subtle contextual contingency outside of learners' primary focus of attention. This manipulation also enabled us to present language stimuli in the visual rather than auditory modality, thereby improving time-locking precision for event-related potential analyses.

Using this design, we addressed two key questions raised by Kamide's result. First, we asked whether learners show sensitivity to a specific context when the correlation between syntactic structure and background cues is probabilistic. In Kamide's study, syntactic structure was deterministically predictable based on speaker identity, with each speaker *always* producing a given type of sentence. However, in everyday language, the correlation between syntactic structure and environmental context is likely to be much weaker. Thus, the first goal of the present study was to examine whether learners showed sensitivity to background cues when they occurred only probabilistically. Such evidence could conceivably demonstrate that language users have the ability to extract signal from noise in order to make predictions during online language processing. Secondly, we examined whether this learning was implicit in nature. Kamide demonstrated that learners became sensitive to the relationship between structural preference and speaker identity, but did not assess the extent to which conscious awareness of this contingency may have contributed to observed learning effects. Given that there was a one-to-one correspondence between speaker identity and syntactic structure, it is possible that participants in Kamide's study became explicitly aware of this relationship. In the present study, if participants remain unaware of the contingency between font color and sentence structure while still showing sensitivity to this contingency, this would point to the involvement of implicit learning mechanisms, similar to mechanisms that have been shown to drive syntactic priming.

We used event-related brain potentials (ERPs) as the main dependent measure of whether learners became sensitive to the contingency between font color and sentence structure. Because ERPs do not require an overt behavioral response they are an ideal measure of (potential) implicit learning. Demonstrating that ERPs to garden-path structures differ as a function of font color would provide evidence of learners' sensitivity to background cues—to which little attention is generally allocated—during online language processing.

Previous ERP studies of garden-path sentences have demonstrated that words that are inconsistent with the preferred or usual sentence structure elicit P600 effects (e.g., Osterhout & Holcomb, 1992; Osterhout, Holcomb & Swinney, 1994). For example, the word "to" in garden-path sentences such as "The broker persuaded *to* sell the stock was sent to jail," elicited a larger P600 effect relative to non-ambiguous control sentences (e.g., "The broker hoped *to* sell the stock"). The P600 is a late centro-parietal ERP positivity elicited by syntactic violations, and has been proposed to index syntactic reanalysis and repair and/or syntactic integration difficulties (Friederici, 2002, 2011; Hagoort & Brown, 2000). The presence of P600 effects in garden-path sentences suggests that readers commit themselves to a single syntactic analysis during online sentence processing, typically a simple active interpretation. Encountering "to" in a garden-path sentence therefore requires revision of the more expected or preferred syntactic analysis, eliciting an enhanced P600 component (Osterhout, McLaughlin & Bersick, 1997).

Following one of these early ERP studies (Osterhout & Holcomb, 1992), we presented participants with garden-path ("GP"), normative control, and "GP-Lure" sentences, such as the following:

1. The salesman persuaded the customer to buy the car. (Normative)
2. The salesman persuaded to conceal the sale was sent to jail. (GP)
3. *The salesman hoped to make the sale was given a raise. (GP Lure)

GP-Lure sentences were similar to GP-sentences in that they began with a noun phrase, a verb used intransitively, and the infinitival marker *to* (e.g., "The salesman hoped to…"). However, the verbs selected for use in GP-Lure sentences cannot be passivized, and thus the sentence becomes grammatically unacceptable at the point of the second auxiliary verb (e.g., *was* in Sentence 3).

As in previous studies (Osterhout & Holcomb, 1992), we extracted two main types of critical events for ERP analyses (Figure 1). The first event consisted of the infinitival marker *to* in GP and control sentences (see Table 1 for examples). *To* in GP sentences represents the point of disambiguation, marking the absence of a noun phrase and providing the first indication that a simple active interpretation of the sentence is not possible. Thus, we hypothesized that *to* should elicit a larger P600 effect when it occurs in GP sentences, following a transitively-biased verb used in an intransitive context, compared to when it occurs in control sentences following an intransitive verb. The second event type of interest consisted of the auxiliary verbs (i.e., *was*), in both GP and GP-Lure sentences. In GP-Lure sentences, *was* represents a violation, at which point the sentence becomes grammatically unacceptable. When *was* is encountered, backtracking and reanalysis are likely to occur as participants review the preceding sentence context in order to make an acceptability judgment. In contrast, *was* in GP sentences is consistent with an acceptable syntactic analysis. Thus, we expected to observe an enhanced P600 to *was* in the GP-Lure condition relative to the GP condition, demonstrating that participants have detected the syntactic anomaly presented in GP-Lure sentences and are engaging in reanalysis and repair.

Critically, but unbeknownst to participants, font color probabilistically predicted the presence of a garden-path structure, with 75% of garden-path sentences (and 25% of normative sentences) appearing in a given font color. As a direct test of the main hypotheses of the study, we compared both *to* and *was* within the GP sentence condition as a function of font color. In GP sentences, *to* represents the point of disambiguation, the first point in the sentence that is inconsistent with the generally preferred, simple active interpretation; the verb *was* represents the point of syntactic ambiguity resolution, providing a necessary attachment for the main clause (Figure 1). Without this auxiliary verb clause, the preceding sentence would be ungrammatical (e.g., "*The salesman persuaded to conceal the sale."). Processing of these structures may be implicitly influenced by background cues. For example, processing of *was* could potentially be facilitated when GP sentences appear in the GP-Frequent relative to the GP-Rare color, as color would reinforce the need for a passivized relative clause interpretation. Thus, we hypothesized that we would observe an ERP difference to *to* and/or *was* in GP sentences as a function of color, demonstrating that participants became sensitive to the color-structure contingency. Because participants are likely to acquire this sensitivity only with sufficient exposure, we included experiment half as a factor and analyzed ERP effects separately for the first and second half of trials. We hypothesized that robust color-associated effects would be observed in the second half of the experiment. Finally, we also assessed learners' explicit knowledge of the color-structure contingency in order to examine whether this learning was implicit.

Methods

Participants

Thirty-eight native English speakers (26 women) were recruited as paid volunteers at Northwestern University to participate in this experiment. Participants were between 18 and 30 years old (*M* = 20.4 years, *SD* = 2.2 years), and reported normal vision and no history of neurological problems. Two participants were excluded from all analyses due to poor performance on the grammaticality judgment task (<35% of grammatical violations classified correctly). An additional four participants were excluded due to poor EEG data quality (*n* = 3) or EEG technical problems (*n* = 1), resulting in a final sample of 32 participants for all behavioral and EEG analyses.

Stimuli

A total of 600 sentences were presented to each participant. Examples of each sentence type are shown in Table 1. Of the total set, 240 were garden-path sentences that contained temporary syntactic ambiguities ("GP" condition). An additional 240 sentences were paired normative versions of the GP sentences ("normative" condition). The first three words of each pair of GP and Normative sentences were identical, but the sentences diverged after this point. Together, these 480 sentences (in the GP and normative conditions) comprised the critical sentences of the current experiment. Each critical sentence contained a past participle form of a verb (e.g., *persuaded*) that can act either as the main verb of a sentence (see "Normative" example, Table 1), or as the verb in a reduced relative clause (see "GP" example, Table 1).

These verbs are transitively-biased; that it, they are most often used transitively, in an active form that requires a noun phrase acting as a direct object (e.g., Normative example). This type of sentence is consistent with the typical or preferred analysis that most comprehenders construct when presented with the sentence fragment "*The salesman persuaded…*". However, these verbs can also be used intransitively in a passive form that does not require a direct object (e.g., GP example). This alternative analysis requires passivizing the verb and attaching it to a reduced relative clause. This analysis is atypical or less expected, and forces the comprehender to reanalyze the sentence when the preferred analysis proves to be inappropriate, resulting in a garden-path effect. Each pair of GP and Normative sentence versions began with the same initial context and contained the same initial verb. Verbs in Normative sentences were used transitively, and thus the sentence was resolved using a preferred or expected structure without any syntactic ambiguity. In contrast, verbs in GP sentences were used intransitively, requiring a less expected, reduced relative clause interpretation.

In addition to these critical sentences, 80 grammatically unacceptable sentences were presented. Half of these sentences were designed to mimic the structure of GP sentences (see "GP-Lure" example, Table 1). However, the initial verbs chosen for GP-Lure sentences cannot be used in a reduced relative clause, allowing for only a simple active analysis. Thus the sentence becomes grammatically unacceptable at the point of the second auxiliary verb (e.g., *was*). The inclusion of GP-Lure sentences was designed to increase the difficulty of the grammaticality judgment task, forcing participants to read each sentence thoroughly for comprehension rather than simply attending to superficial sentence structure. The other half of the grammatically unacceptable sentences began as simple active sentences that became unacceptable with the addition of a second auxiliary verb introducing a new clause (see "Salient" example, Table 1). Thus, the structure of the initial context of these sentences resembles that in the Normative condition. In the context of the experiment, these types of sentences produce grammatical violations that are relatively more salient than the GP-Lure sentences ("Salient" condition). Finally, an additional 40 Control sentences were presented, which followed a nonanomalous simple active structure (see "Control" example, Table 1). These sentences allowed us to directly compare ERPs elicited by the infinitival marker *to* following transitive versus intransitive verbs, as will be described in more detail under ERP methods.

Sentences were presented visually one word at a time on a computer monitor. Of the total set of 600 sentences, half were presented in blue and half in red for each participant, with a white background. The critical experimental manipulation involved the relative proportion of sentences presented in each color in the GP and Normative conditions. For each participant, 75% of GP sentences and 25% of Normative sentences were presented in one color (subsequently referred to as the "GP-Frequent" color), while 25% of GP sentences and 75% of Normative sentences were presented in the alternative color (i.e., the "GP-Rare" color). The color (red or blue) assigned to each condition was counterbalanced across participants. The remaining non-critical sentences (violation and filler sentences) were presented in both colors in equal proportions. Thus, within the GP-Frequent color condition, 60% of sentences were GP, and within the GP-Rare color condition, 20% of sentences were GP (see Table 2 for exact trial numbers in each condition).

Procedure

Participants were tested in a single session. After EEG setup, participants were seated in an electrically shielded and sound-attenuated chamber. They were instructed that their task was to read sentences displayed on a computer screen and to decide whether each sentence was grammatically acceptable or not. They were informed that the goal of the experiment was to investigate the effect of color on language processing. No further information related to color was given. Eight practice trials were presented to ensure that the participants understood the task before the main experiment began. Examples of all types of sentences were included in the practice (GP, Normative, and violations). Sentences used for practice were not included in the main experiment. If necessary, it was clarified that GP sentences are generally considered to be grammatically acceptable, even though they may be more confusing or difficult to comprehend than other types of sentences.

Each sentence began with the presentation of a fixation cross for 1000 ms, presented in the same color as the rest of the sentence. Each word was then presented for a duration of 350 ms, with a 150-ms interstimulus interval. The final word in each sentence ended with a period. A cue ("Correct or Incorrect?") then prompted participants to make a grammaticality response. Reaction times were measured relative to the onset of this cue. Once the response was entered, the next trial began. Participants were given breaks after every 50 trials.

After finishing the experimental task, participants completed a questionnaire designed to assess the extent to which they were aware of the contingency between font color and grammatical structure. The questionnaire listed nine new sentences that conformed to the different types of sentence structures presented during the main experiment. Three of the nine sentences were GP sentences. Participants were asked to rate whether they thought each sentence would have been more likely to appear in red or blue in the context of the experiment, using a 1–9 scale with 5 indicating no color preference. Ratings were averaged for the three GP sentences and compared to the middle value of the scale (5), yielding an objective measure of color contingency awareness for each individual. Scores on this measure significantly greater than zero would provide evidence that participants had obtained some degree of awareness about the color-structure contingency.

Participants were then interviewed verbally to obtain a subjective or qualitative measure of awareness of the contingency. They were asked whether they noticed any pattern between the color and the type of sentence, and if so, to describe the pattern. They were then asked to guess whether they thought the GP sentences had appeared more often in red or blue.

EEG Recording and Analysis

EEG was recorded at a sampling rate of 512 Hz from 32 Ag/AgCl-tipped electrodes attached to an electrode cap using the 10/20 system. Recordings were made with the Active-Two system (Biosemi, Amsterdam, Netherlands), which does not require impedance measurements, an online reference, or gain adjustments. Additional electrodes were placed on the left and right mastoid, at the outer canthi of both eyes and below the right eye. Scalp signals were recorded relative to the Common Mode Sense (CMS) active electrode and then re-referenced offline to the algebraic average of the left and right mastoid. Left and right horizontal eye channels were re-referenced to one another, and the vertical eye channel was re-referenced to FP1.

ERP analyses were carried out using EEGLAB (Delorme & Makeig, 2004). Data were band-pass filtered from 0.1 to 40 Hz. Epochs time-locked to critical events, as described below, were extracted from −200 to 1200 ms. Large or paroxysmal artifacts or movement artifacts were identified by visual inspection and removed from further analysis. Data were then submitted to an Independent Component Analysis (ICA), using the extended runica routine of EEGLAB software. Ocular and channel artifacts were identified from ICA scalp topographies and the component time series, and removed. ICA-cleaned data were then subjected to a manual artifact correction step to detect any residual or atypical ocular artifacts not removed completely with ICA. When necessary, bad recording channels were identified, excluded from all ICA decompositions, and interpolated later (average of 1.5 channels per participant; range = 0–5).

As described in the Introduction, ERPs were time-locked to the infinitival marker *to* in GP, Normative and control sentences and auxiliary verbs (i.e., *was*), in both GP and GP-Lure sentences. Only trials to which participants made a correct grammaticality response were included in the analysis. Epochs were plotted to 1200 ms poststimulus, with a 200-ms baseline. The time interval for all P600 analyses was selected from 500–900 ms poststimulus, based on previous findings (e.g., Friederici, 2002) and visual inspection of the waveforms. As a direct test of the main hypothesis of the study, we compared ERPs to the infinitival markers and auxiliary verbs within the GP sentence condition as a function of font color. For infinitival markers, a time window from 300–700 ms was selected to best capture potential ERP differences based on visual inspection of the waveform. For auxiliary verbs, a broad time interval was selected from 300 ms to the end of the averaging epoch, capturing the sustained nature of the effect. A second analysis using a time interval from 300–500 ms was also conducted in order to examine the earliest part of this effect. A parallel analyses to the one described above was also conducted on Normative sentences, contrasting ERPs to the infinitival marker *to* (a syntactic element that appeared in all Normative sentences) as a function of color. Mean amplitude values were calculated for each scalp channel. For each analysis, a set of 24 electrodes (F7, F3, FC5, FC1, T7, C3, CP5, CP1, P7, P3, O1, PO3, F8, F4, FC6, FC2, T8, C4, CP6, CP2, P8, P4, O2, PO4) was entered into a repeated-measures ANOVA, with condition, hemisphere (left, right), anterior/posterior (frontal, fronto-temporal, temporal, central, parietal, occipital), and lateral/medial (lateral, medial) included as factors. Experiment half (1^{st}, 2^{nd}) was included as an additional factor in the GP-color analyses, as well as the GP versus control P600 analysis. Greenhouse–Geisser corrections were applied for factors with more than two levels.

Behavioral Data Analysis

Effect of contextual color on accuracy was initially examined using a 3-way ANOVA with experiment half (1^{st}, 2^{nd}), font color (GP-Frequent, GP-Rare), and condition (GP, Normative) as factors. Experiment half was not found to significantly modulate the effect of color on the condition effect ($F(1,31)= 0.98$, $p = 0.33$) and was subsequently dropped as a factor.

Similarly, reaction time data were analyzed using a 3-way ANOVA with experiment half (1^{st}, 2^{nd}), font color (GP-Frequent, GP-Rare), and condition (GP, Normative) as factors. Reaction times were analyzed by computing the median reaction time for each participant within each condition, excluding incorrect responses.

Results

Behavioral Results

Participants performed moderately well on the grammaticality judgment task. Overall accuracy on the task was 95.8% (SD = 3.28%). Grammatically acceptable sentences (GP, Normative, and Control sentences combined) were classified correctly at a rate of 98.2% (SD = 1.76%), whereas grammatical violation sentences were classified correctly at a rate of only 82.3% (SD = 14.7%). Within the grammatically unacceptable condition, participants were significantly less accurate at classifying GP-Lure sentences compared to Salient Violation sentences (GP-Lure: M = 76.9%, SD = 17.2; Salient Violation: M = 87.7%, SD = 13.0%; $F(1,31) = 60.1$, $p < 0.001$), suggesting that GP-Lure sentences may have been mistaken for grammatically correct GP sentences on some proportion of trials. Thus, the grammaticality judgment task was sufficiently challenging, as intended.

Of the critical experimental sentences, GP sentences were classified significantly less accurately than Normative sentences, though performance for both conditions was near ceiling and the overall difference was small (GP: M = 96.3, SD = 4.10%; Normative: M = 98.9%, SD = 1.64%; $F(1,31) = 14.3$, $p = 0.001$). Most importantly, grammatical judgments were significantly modulated by contextual color (Color x Sentence Condition: $F(1,31) = 4.30$, $p = 0.046$). This interaction indicates that, across the two critical conditions, sentences were more likely to be judged as acceptable when presented in their usual font color, as shown in Figure 2. Indeed, GP sentences were numerically more likely to be classified as acceptable when appearing in the GP-Frequent color, whereas Normative sentences were numerically more likely to be classified as acceptable when appearing in the GP-Rare color (i.e., the color most frequently used to present Normative sentences). Although the interaction was significant, tests of simple effects comparing accuracy between the two color conditions within each sentence condition did not yield significant results (Color effect within GP condition: $F(1,31) = 2.16$, $p = 0.15$; Color effect within Normative condition: $F(1,31) = 0.87$, $p = 0.36$). Performance was near ceiling in all conditions and thus overall sensitivity of this measure was relatively low. Nonetheless, the overall pattern of the data indicates that a match between usual font color and sentence structure increased acceptability rates across the two critical sentence types, whereas a mismatch decreased acceptability.

Reaction time data revealed that GP sentences were responded to significantly more slowly than Normative sentences ($F(1,31) = 12.8$, $p = 0.001$). The average RT to GP sentences was 625 ms (*SEM* = 54) and to Normative sentences was 543 ms (*SEM* = 53). This result indicates that GP sentences were more difficult to process overall. This effect was not significantly modulated by color ($F(1,31) = 2.50$, $p = 0.12$), which was not unexpected, given that end-of-sentence grammatical acceptability judgments are unlikely to provide a sensitive measure of processing speed.

ERP Results

Infinitival marker *to* in GP sentences versus control sentences—In contrast to our hypothesis, overall the infinitival marker *to* in GP sentences versus control sentences did not elicit a significantly different ERP during the P600 time interval ($F(1,31) = 0.24$, $p = 0.62$; all distributional interactions $p > 0.19$; Figure 3). However, one possibility is that repeated exposure to garden-path sentences may have led participants to expect or anticipate the garden-path structure (i.e., the marker “to” following a transitively-biased verb such as *persuade*), leading to a reduction of the P600 effect. Consistent with this possibility, we found that the P600 effect was significant in the first half of the experiment only (Experimental Half x Condition: $F(1,31) = 6.80$, $p = 0.014$; Condition Effect within First Half: $F(1,31) = 5.60$, $p = 0.024$; Figure 3). This P600 effect showed a typical posterior distribution (Condition x Anterior/Posterior: $F(5,155) = 3.21$, $p = 0.025$). In contrast, there was no significant P600 effect in the second half of the experiment, with a trend towards an opposite polarity effect (Condition Effect: $F(1,31) = 3.44$, $p = 0.073$; Figure 3). This result suggests that participants initially experienced some degree of processing or integration difficulty when the marker “*to*” followed the initial transitively-biased verb in a GP sentence, but that this processing difficulty was eliminated as they became habituated to this type of structure.

Auxiliary verb *was* in GP sentences versus GP lures—Consistent with our hypothesis, the auxiliary verb *was* in grammatically unacceptable GP-Lure sentences elicited a significantly larger P600 effect than auxiliary verbs in the grammatically acceptable GP sentences (Condition: $F(1,31) = 46.9$, $p < 0.001$; Figure 4). The P600 effect showed a typical posterior and medial distribution (Condition x Anterior/Posterior: $F(5,155) = 34.4$, $p < 0.001$; Condition x Lateral/Medial: $F(1,31) = 22.4$, $p < 0.001$). This finding provides a manipulation check, indicating that ERPs show expected effects of syntactic violation processing. This result also demonstrates the time-course of syntactic violation processing, as only GP-Lure sentences contain a syntactic violation.

Direct test of central hypothesis: Effect of color contingency on GP sentence processing—As a direct test of our hypothesis, we tested whether color influenced ERPs to GP sentences. We analyzed ERP data both at the point of the infinitival marker *to* as well as subsequently at the point of the auxiliary verb *was*.

Effect of color contingency on processing of infinitival marker to in GP sentences: The P600 effect to the infinitival marker *to* in GP sentences versus control sentences did not interact significantly with the color manipulation, either overall across the experiment ($p = 0.85$) or within either experimental half (both p values > 0.5). We propose that learning effects worked against one another over the course of the experiment, precluding significant interactions with color. That is, in the first half of the experiment, participants showed a P600 to GP sentences as they had not yet become habituated to these types of sentences, but likely had not yet become sensitive to the color contingency. By the second half of the experiment, participants had likely acquired the color contingency, but by this time had adapted to the GP structure, no longer showing a significant P600 effect to GP sentences. Thus, color did not impact the P600 in either the first or second experimental half.

Effect of color contingency on processing of auxiliary verb was in GP sentences: Whereas color had no effect on processing of infinitival markers, it significantly impacted processing of auxiliary verbs. In the second half of the experiment, auxiliary verbs presented in the GP-Rare color elicited a sustained negative shift relative to auxiliary verbs presented in the GP-Frequent color (Figure 5). The effect began at approximately 300 ms and persisted until the end of the averaging epoch, following the onset of the subsequent word. To quantify this effect, we selected a broad time interval of 300 to 1200 ms as well as an earlier time interval from 300 to 500 ms.

300 to 1200 ms: In the second half of the experiment, auxiliary verbs appearing in the GP-Rare color elicited a significant negativity relative to verbs appearing in the GP-Frequent color (Half x Color $F(1,31) = 5.88$, $p = 0.021$; Follow-up Color Effect 2nd Half: $F(1,31) = 4.22$, $p = 0.048$). The effect of color was not significant in the first half of the experiment ($F(1,31) = 1.53$, $p = 0.23$). No distributional interactions were significant (all p values > 0.1).

300 to 500 ms: In the second half of the experiment, the negativity to auxiliary verbs in the GP-Rare color remained significant when the analysis was restricted to the earlier time interval (Half x Color: $F(1,31) = 3.96$, $p = 0.055$; Follow-up Color Effect 2nd Half: $F(1,31) = 4.76$, $p = 0.037$). Again, the effect of color was not significant in the first half of the experiment ($F(1,31) = 0.25$, $p = 0.62$). No distributional interactions were significant (all p values > 0.1).

Effect of color contingency on processing of infinitival marker *to* in Normative sentences: A parallel analysis was conducted for ERPs time-locked to the infinitival marker *to* in Normative sentences (Figure 6). Similar to the effect observed for GP sentences, the infinitival marker *to* presented in the GP-Frequent color (i.e., the Normative-Rare color) elicited a sustained negative shift relative to ERPs elicited by *to* presented in the GP-Rare color (i.e., the Normative-Frequent color). This effect was small in amplitude but statistically robust, and showed a similar latency and distribution to the GP color effect. Thus, for both GP and Normative sentences, processing of sentences presented in the unexpected or deviant color (relative to the respective comparison condition), respectively, elicited a sustained negativity.

300 to 1200 ms: Across both experimental halves, the infinitival marker *to* presented in the GP-Frequent color elicited a sustained negativity compared to the GP-Rare color (Color: $F(1,31) = 7.80$, $p = 0.009$; Figure 6). This effect did not interact significantly with experimental half ($p > 0.9$), though it was numerically larger in the second half.

300 to 500 ms: Across both experimental halves, the negativity was significant when the analysis was restricted to the earlier time interval ($F(1,31) = 6.86$, $p = 0.014$). Again, the effect did not interact significantly with experimental half ($p > 0.9$).

Questionnaire Data

Participants' performance on the color-rating task for GP sentences was not significantly above chance (M = 0.094, SD = 1.22; $t(31) = 0.44$, $p = 0.67$). That is, participants did not endorse GP sentences as being more likely to appear in the GP-Frequent color compared to the GP-Rare color. Based on this measure, there is no evidence that participants became consciously aware of the color-structure contingency. The interview data (below) were largely consistent with this outcome.

We also addressed whether performance on the color-rating task correlated with the negative ERP effect observed to auxiliary verbs in GP sentences by including performance on the color-rating task as a covariate. Performance on the color-rating task did not significantly interact with the color effect during either the 300–500 ms time interval (Awareness Score x Color: $F(1,30) = 0.15$, $p = 0.70$) or the broader 300–1200 ms time interval (Awareness Score x Color: $F(1,30) = 0.73$, $p = 0.40$). In both analyses, the effect of color remained significant when the awareness measure was included as a covariate in the model (Color Effect: 300–500 ms: $F(1,30) = 4.73$, $p = 0.038$; 300–1200 ms: $F(1,30) = 4.44$, $p = 0.044$). Based on these results, there is no evidence that explicit knowledge of the color-structure contingency contributed to the observed ERP negativity.

Verbal Interview

Of the 32 participants, only 4 participants claimed to have noticed any patterns between the color of the sentence and the structure of the sentence. When questioned further, only 2 of these 4 participants were able to describe a pattern in the data that could be construed as accurately describing the actual color-structure contingency (e.g., "red sentences seemed gawkier and more awkward" and "blue was more complicated and red was more simple"). The remaining 2 participants provided explanations that were unrelated to the actual color-structure manipulation (e.g., "red sentences contained more intense or severe words"). Therefore, only 2 of the 32 participants could be considered to be subjectively aware of the color contingency based upon the questionnaire data. All previously reported effects related to color contingency, for both GP and Normative sentences, remained significant when these two participants were excluded.

In the final stages of the interview, participants were informed that GP sentences (described as those that "were more confusing or which led you initially into one interpretation before you realized that there may be a second interpretation") appeared more often in one color. They were then asked to guess which color they believed the GP-Frequent color to be. Although many participants initially expressed reluctance to make a guess, 21 of the 32 participants ultimately selected the correct color, though typically with low confidence. This level of performance is marginally above chance according to binomial probability statistics (binomial $p(x \geq 21/32) = 0.055$; expected number of correct responses for $p < 0.05 = 22$). This finding suggests that a subset of participants had some ability to retrospectively identify the color-structure contingency, though most were likely not aware of this contingency either at that time of online processing or later. The negative ERP effect elicited by auxiliary verbs in GP sentences did not significantly differ between participants who correctly identified the color-structure contingency and those who did not (300–500 ms: Group x Color: $F(1,30) = 0.26$, $p = 0.61$; 300–1200 ms: $F(1,30)= 0.001$, $p = 0.97$). Thus, we again failed to find evidence that any measurable degree of explicit awareness contributed to or modulated the observed ERP negativity.

All participants except the first 5 ($n = 27$) were also asked to rate how much attention they paid to the color of the sentences on a 1–10 scale (1 = no attention; 10 = highest level of attention). The average rating given was 3.33 (SD = 2.03), indicating that most participants likely allocated low amounts of attention to font color.

Discussion

In the present study, we showed that people were implicitly sensitive to subtle, probabilistic background cues during online language processing. Participants read through a large set of sentences, some of which contained a difficult-to-integrate, garden-path structure whereas others followed a readily interpretable, preferred structure. Unbeknownst to participants, the color of text presentation probabilistically predicted the type of sentence that was shown. Objective and subjective measures indicated that the vast majority of participants had no conscious awareness of the relationship between font color and sentence structure. Nonetheless, with sufficient exposure to the stimuli, ERPs to GP sentences differed significantly as a function of whether presentation occurred in the GP-Frequent color or the

GP-Rare color. Specifically, a sustained negativity with an onset of approximately 300 ms was observed to auxiliary verbs of GP sentences, representing the point of syntactic ambiguity resolution in the GP-Rare color relative to the GP-Frequent color. A parallel result emerged for Normative sentences, in which ERPs to the infinitival marker *to* in the GP-Frequent color elicited a sustained negativity (i.e., the Normative-Rare). These findings indicate that participants became implicitly sensitive to the hidden color-structure contingency during online language processing.

As reviewed in the Introduction, previous work has shown that people are highly sensitive to recent linguistic input, showing rapid adaptations and changes in expectancy as a consequence of exposure to specific linguistic patterns. For example, repeated exposure to GP sentences causes language users to expect these types of sentences, reducing the processing disadvantage that these sentences engender, as measured through reaction times (Fine et al., 2013). Prior research has also shown that these adaptations do not simply reflect overall changes in the cumulative statistics amassed over recent experience, but can be context-specific. For example, as reviewed earlier, Kamide (2012) demonstrated speaker-specific syntactic adaptation effects, in which learners became sensitive to the identity of the speaker and his/her tendency to produce a given type of syntactic structure.

The present study builds upon and extends these findings, providing evidence that contextual cues influence language processing with a high degree of specificity and subtlety. Our key finding—neural differences in sentence processing as a function of presentation color—is especially striking given several key aspects of our design that differ from previous studies showing syntactic adaptation effects. First, we presented sentences visually and manipulated color of text presentation, whereas previous studies examining context-specific language adaptation effects have generally manipulated speaker identity (e.g., Kamide, 2012; Creel et al., 2008). Outside of the laboratory, participants have presumably had considerable experience tracking different speakers during conversations, and thus are likely to attend to speaker identity when processing spoken language. In contrast, the color of written text is generally irrelevant, and participants are less likely to allocate attention to this dimension. A second related point is that participants' attention was not explicitly drawn to the font color in this experiment, and most participants reported allocating low levels of attention to this dimension. Thus, the ability to register the contingency between font color and sentence structure is especially remarkable, given that presentation color is typically of low relevance and was not likely to be a feature that received extensive processing in this experiment. Finally, in the current study, the relationship between presentation color and syntactic structure was probabilistic (75%/25%), rather than all-or-none (100%/0%), as in Kamide's (2012) study. Thus, sensitivity to font color required extracting a weak signal from a considerable amount of noise. In sum, the finding that ERPs differed as a function of font color demonstrates that people are capable of acquiring highly subtle, probabilistic, and largely unattended contingencies during online language processing.

Several lines of evidence suggest that learners acquired the contingency between color and structure implicitly—that is, without conscious awareness of having acquired this knowledge. Objective evidence for this claim comes from chance-level performance on the color-rating task, administered after the main experimental task. In other words, when presented with an example of a GP sentence, participants could not accurately determine whether it was more likely to have appeared in one color over the other (i.e., the GP-Frequent versus GP-Rare color). If participants had become aware of the relationship between color and sentence structure, they should have been able to perform this task at above-chance levels, even if unable to articulate this knowledge. It is also worth noting that the vast majority of participants ($n = 32/34$) were unable to correctly verbalize the relationship between color and sentence structure in even a vague way. Although this piece of evidence must be interpreted with the caveat that verbal reports can often underestimate a learner's degree of explicit knowledge (e.g., Shanks & St. John, 1994; Dienes & Scott, 2005), it provides some additional assurance that any role of explicit knowledge in learning the color-structure contingency was likely to be minimal. The evidence that learners were not consciously aware of the color-structure contingency is consistent with the general idea in the literature that syntactic adaptation effects are a form of implicit, rather than explicit, learning (e.g., Segaert & Hagoort, in press; Fine et al., 2013; Fine & Jaeger, 2013; Bock & Griffin, 2000; Bock et al., 2007; Luka & Barsalou, 2005). As reviewed in the Introduction, most of the direct evidence for this idea comes from syntactic priming studies of production (e.g., Bock et al., 1992; Ferreira et al., 2008; Chang et al., 2000; 2006). The present findings indicate that implicit learning also contributes to syntactic adaptation effects in an entirely different paradigm, one which involves learning the contingencies between the visual appearance of a sentence and its syntactic structure, and which involves language comprehension rather than production.

Event-related potentials were the main dependent measure in the present study, and represent the primary source of evidence that learners became sensitive to the color-structure contingency. However, we also found significant behavioral evidence of this sensitivity. Although acceptability judgments were near 100% for both GP and Normative sentences, a significant interaction indicated that font color differentially influenced acceptability judgments for GP versus Normative sentences (Figure 2). In other words, the probability that a sentence would be judged as acceptable increased when the font color matched the color typically used for that type of sentence (GP/Normative). One potential explanation for this finding is that presenting an initial sentence stem in the GP-Frequent color biases participants to interpret the ambiguous part of the sentence as conforming to the typical GP structure, increasing the likelihood that they will initially parse the past participle verb as a reduced relative clause. If the sentence ultimately conforms to these expectations (as in a GP sentence presented in the GP-Frequent color), this would lead more quickly to a clear understanding of the sentence, increasing grammatical acceptability rates. In other words, experiencing a match between the structure and color of a sentence based on prior experience facilitates processing, resulting in an increase in processing fluency and influencing grammatical judgments. This explanation is consistent with previous findings showing that passive exposure to grammatically ambiguous sentences increases acceptability ratings of new sentences following the same structures (Luka & Barsalou, 2005; Luka & Choi, 2012). Similar to two-step accounts of the mere exposure effect (e.g., Bornstein & D'Agostino, 1994; Jacoby, Kelley, & Dywan, 1989), repeated exposure increases perceptual fluency (e.g., Jacoby & Dallas, 1981; Jacoby & Witherspoon, 1982), which could then contribute to changes in evaluative ratings (Reber, Winkielman & Schwarz, 1998).

Presumably, implicit learning should facilitate language processing at a behavioral level by allowing comprehenders to form accurate predictions about incoming input. One limitation of the present study is that we did not directly assess such functional benefits. Our main behavioral measure consisted of end-of-sentence grammatical acceptability judgments, which do not provide a sensitive measure of processing speed. We speculate that with the use of fine-grained behavioral measures, such as a sliding window reading time procedure, it could be shown that GP sentences presented in the GP-Frequent color are processed more quickly and efficiently than GP sentences presented in the GP-Rare color. Such a finding would provide evidence that sensitivity to context during language processing allows participants to adapt their expectations of incoming input in order to optimize online processing. Addressing this question is an exciting challenge for future research.

ERPs to the Disambiguating Infinitival Marker *to*

Based on an early study of syntactic ambiguity processing (Osterhout & Holcomb, 1992), we hypothesized that the disambiguating infinitival marker *to* in GP sentences, in which a transitively-biased verb is used in an intransitive context, would elicit a P600 effect. We reasoned that because the initial verb in these sentences (e.g., *persuade*) is normally used transitively, the parser would expect a noun phrase to follow the verb. Encountering *to* in this context would violate this expectation, requiring a reanalysis of the previous structure and eliciting a P600.

Interestingly, this predicted P600 effect was observed only during the first half of the experiment. By the second half of the experiment, we found no significant difference in P600 amplitude between *to* occurring in GP sentences relative to control sentences. This finding suggests that participants initially preferred the more typical active syntactic analysis when encountering the initial transitive verb fragment (e.g., *The salesman persuaded…*). Thus, they showed a P600 effect to the marker “to” in GP sentences early on in the experiment. However, with more exposure to GP sentences, it appears that participants began to anticipate the GP structure, and no longer committed to an active analysis over a passive reduced relative clause analysis. In other words, repeated exposure to garden-path sentences during the experiment altered participants’ syntactic expectations, such that GP structures were no longer unexpected. After sufficient exposure to GP sentences, participants may have adopted a “wait-and-see” processing strategy for transitive verbs rather than immediately committing to the typical preferred syntactic interpretation, which would result in a processing cost if this expectation were not met. This explanation converges with findings showing that repeated exposure to garden-path sentences can reverse their processing disadvantage, as measured through reading times (Fine et al., 2013). This result provides an additional example of online learning or adaptation during language processing.

Although we found a significant P600 effect during the first half of the experiment, the effect was not significant overall, when trials from both experimental halves were combined. In contrast, Osterhout and Holcomb (1992) found a significant overall P600 effect. One factor that may account for this difference is that a high proportion of garden-path structures in the Osterhout/Holcomb study were not grammatically resolved; they were presented as incomplete, ungrammatical sentence fragments (e.g., *The woman persuaded to answer the* *door*.). Thus in the context of the experimental session, participants likely learned that *to* frequently signaled the presence of a syntactically anomalous sentence, and was thus likely to be perceived as a violation, eliciting a P600. In contrast, when *to* followed a transitive verb in the present study, a grammatically acceptable continuation was always provided. That is, GP sentences never constituted outright syntactic violations. Thus, after sufficient exposure to these types of sentences, participants in our study adapted their expectations for syntactic structure, showing no differences in processing the disambiguating marker *to* in garden-path versus normative sentences.

Functional Significance of the Sustained Negativity

As described above, neural sensitivity to font color was revealed as a sustained negativity to auxiliary verbs (*was*) of GP sentences presented in the GP-Rare color relative to the GP-Frequent color. This ERP effect showed an onset of approximately 300 ms and was maximal over posterior and central electrodes (Figure 5). We also observed a similar effect to Normative sentences, in which the infinitival marker (to) elicited a sustained negativity when presented in the GP-Frequent/Normative-Rare color (Figure 6). This effect cannot be readily linked to any known language components such as the N400 and P600, and may not be language-specific. Rather, it may reflect general implicit learning mechanisms that operate over a range of different types of stimuli.

Early ERP negativities similar to the one we report have been linked with the acquisition of implicit knowledge in a number of previous studies using implicit learning tasks, such as the serial reaction time and the artificial grammar learning tasks (Fu et al., 2013; Baldwin et al., 1997; Schankin et al., 2011). For example, in a study conducted by Fu and colleagues (2013), participants were presented with a sequence of letters composed of standard and deviant triplets (e.g., X-P-V) and instructed to respond as quickly as possible to each letter. As part of the *process dissociation procedure* (PDP), a method used to isolate implicit and explicit knowledge (cf. Jacoby, 1991), participants then completed both inclusion and exclusion tests, in which they were asked to generate targets that appeared both frequently and rarely in training. The authors demonstrated that deviant targets associated with explicit knowledge elicited larger N200 and P300 components, whereas deviant targets with implicit but not explicit knowledge elicited an N200 effect alone. Fu and colleagues concluded that the acquisition of implicit knowledge is indexed by the N200 effect, while explicit knowledge is additionally reflected in the later P300 component.

Baldwin and colleagues (1997) also used an implicit sequence learning task, in which participants responded to the movement of an object within a grid that followed a complex finite state grammar. Relative to grammatical target movements, target movements that violated the grammar elicited a negative ERP from 200–500 ms. This effect was similar in implicitly-trained learners and explicitly-trained learners who were explicitly informed about the underlying sequence, suggesting that it indexes implicit learning occurring in both groups.

Finally, Schankin and colleagues (2011) used a traditional artificial grammar-learning task (cf. Reber, 1967), in which participants were exposed to sequences of letters constructed according to a finite-state grammar. On each trial, participants were required to memorize the sequence and to type it in correctly. After the initial learning phase, participants were presented with novel sequences that either conformed to or violated the grammar. Ungrammatical letters elicited an enhanced early negativity approximately 120 ms poststimulus relative to grammatical letters.

In sum, across a number of different tasks, items that violated a complex and implicitly learned regularity appeared to elicit an enhanced early negativity. In particular, this component may reflect a mismatch between the actual and anticipated stimulus (cf. Fu et al., 2013), consistent with the general link between the N200 and mismatch detection (Folstein & Van Petten, 2008). Similar mechanisms may at least partially contribute to the observed effects in the present study. When sentences are presented in the typical color, color acts as an implicit cue that can reinforce and facilitate processing of the expected structure. For example, processing of *was* in GP sentences may be facilitated when GP sentences appear in the GP-Frequent relative to the GP-Rare color, as color would reinforce the need for a less typical, relative clause interpretation. In contrast, GP sentences presented in the GP-Rare color (or Normative sentences presented in the GP-Frequent/Normative-Rare color) constitute a mismatch between the color context and the anticipated sentence structure, eliciting an enhanced early negativity.

Conclusions

Our findings support the possibility that "continuous implicit learning is an essential property of the language processing system" (Fine & Jaeger, 2013). We demonstrated that people implicitly detected subtle co-occurrences between environmental contextual cues and syntactic structure. These findings contribute to a body of behavioral evidence showing that language users rapidly make use of the cues from the local environment in order to form predictions about incoming input and optimize comprehension. The current results show that this adaptation can be detected at the neural level, without requiring a concurrent behavioral measure of this type of learning. Sensitivity to background cues was acquired even though the relationship between syntactic structure and context was probabilistic and outside of learners' primary focus of attention, underscoring the powerful and ubiquitous nature of statistical learning mechanisms.

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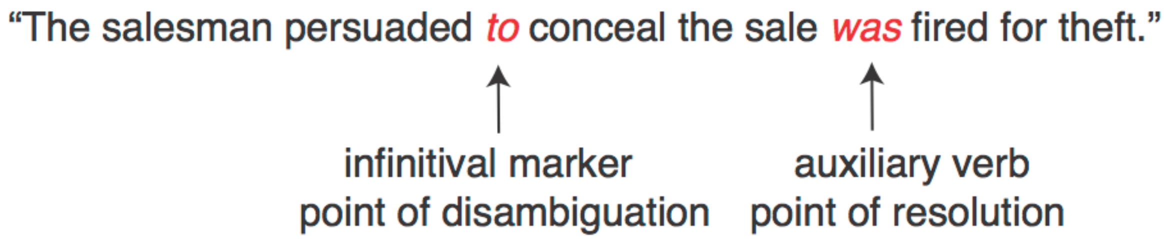

Figure 1.
The two main types of critical events extracted for ERP analyses within the GP sentence condition.

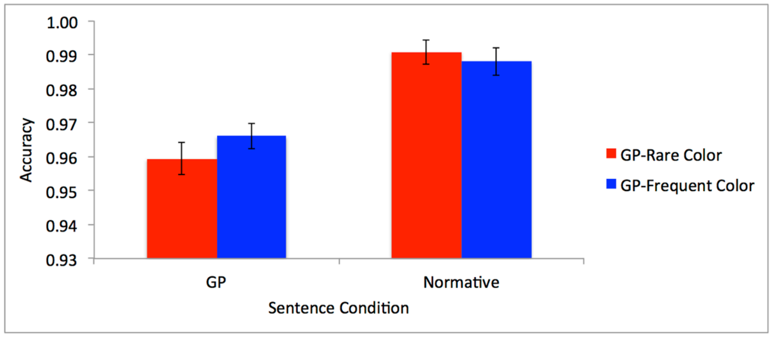

Figure 2.

Grammatical acceptability judgments as a function of sentence condition (GP, Normative) and font color (GP-Rare, GP-Frequent). Error bars show within-subject standard error of the mean, computed by removing between-subject variability across all conditions (Cousineau, 2005).

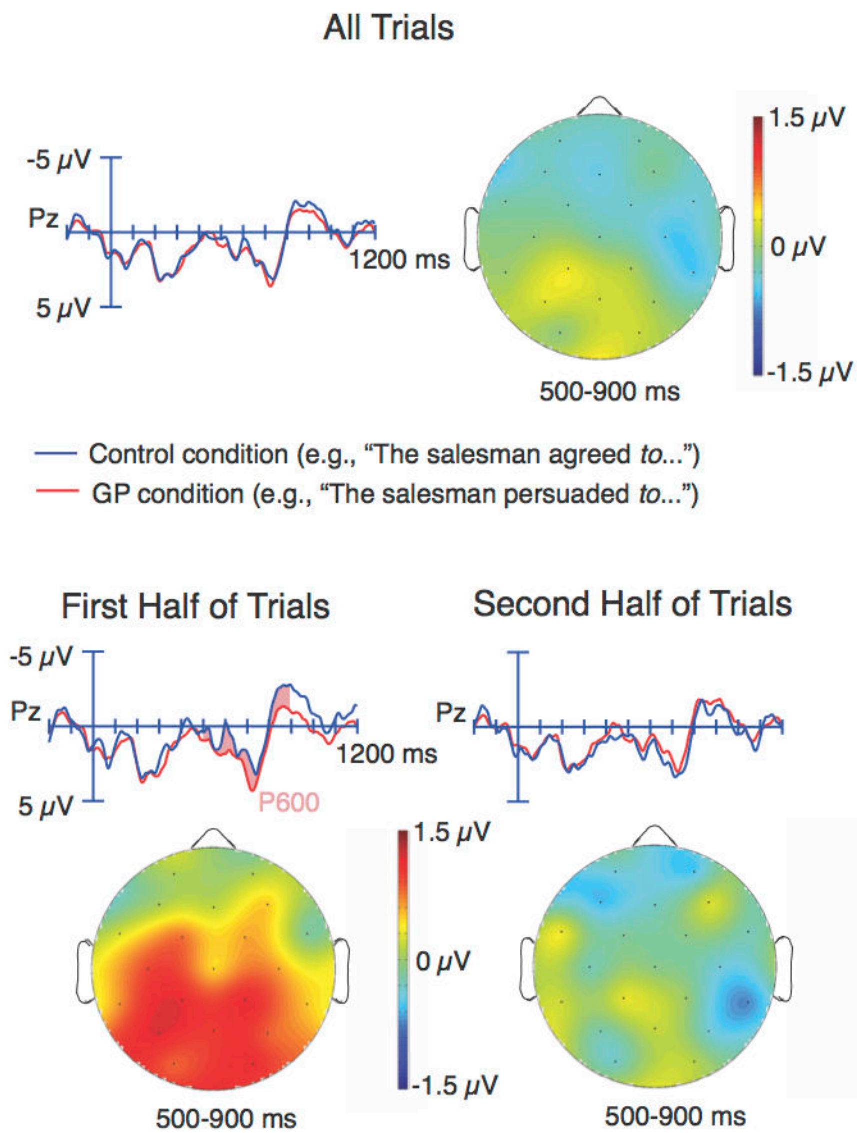

Figure 3.

Grand average ERPs to infinitival marker *to* in GP sentences versus control sentences. A significant P600 effect was found only during the first half of the experiment. The topographic maps shows the average voltage of the effect (GP condition – control condition) across the scalp during the P600 time interval at 500–900 ms poststimulus. Positive potentials are plotted down in this and all subsequent figures.

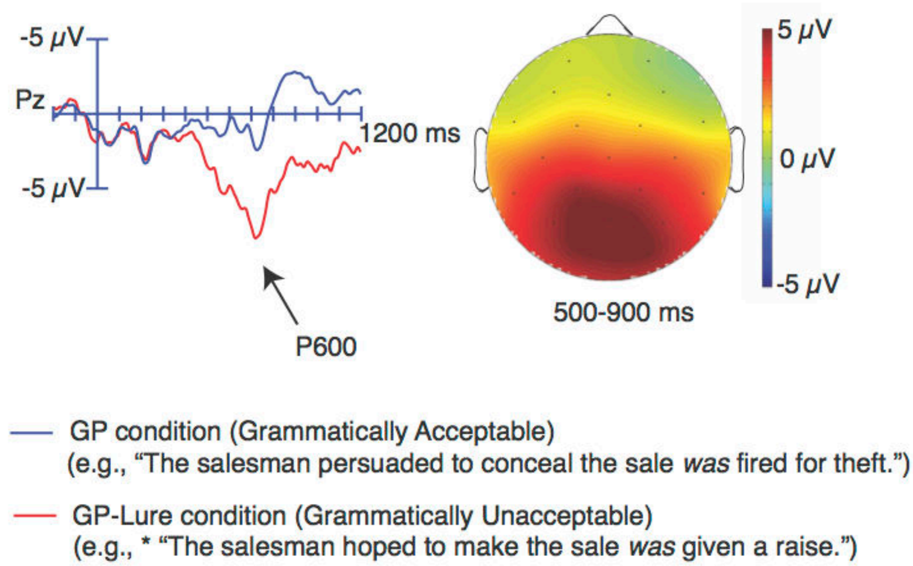

Figure 4.

Grand average ERPs to the auxiliary verb *was* in GP sentences versus GP lures. The auxiliary verb *was* in grammatically unacceptable GP-Lure sentences elicited a significantly larger P600 effect than in grammatically acceptable GP sentences. The topographic map shows the distribution of the P600 effect at 500–900 ms poststimulus (GP-Lure Condition – GP condition).

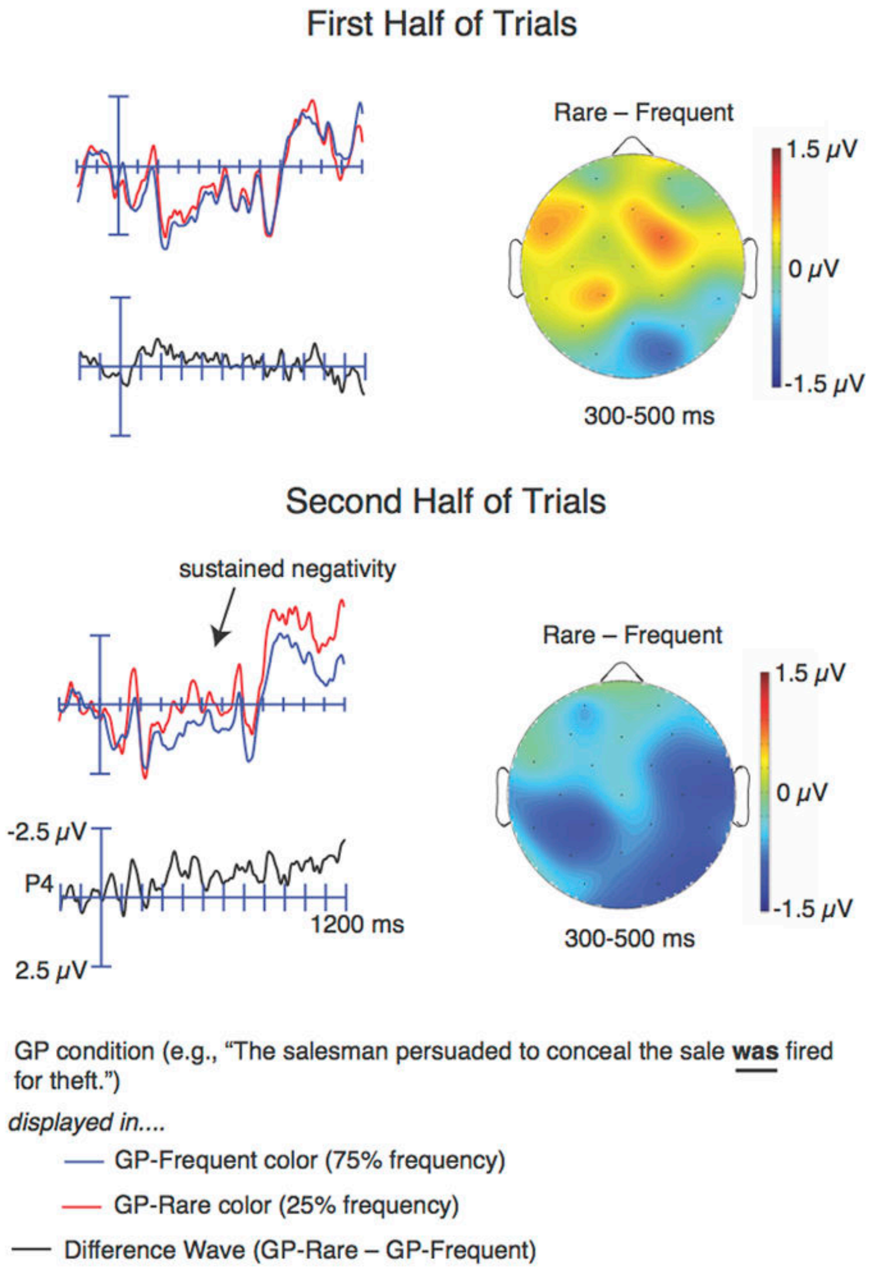

Figure 5.

ERPs to the auxiliary verb, marking the point of syntactic ambiguity resolution in GP sentences presented in the GP-Frequent versus GP-Rare color. ERPs are from electrode P4 and are presented at the same scale. A sustained negativity was observed to GP sentences presented in the GP-Rare color relative to those presented in the GP-Frequent color, but only in the second half of the experiment. The topographic maps display the distribution of the early part of this effect at 300–500 ms poststimulus (GP-Rare – GP-Frequent).

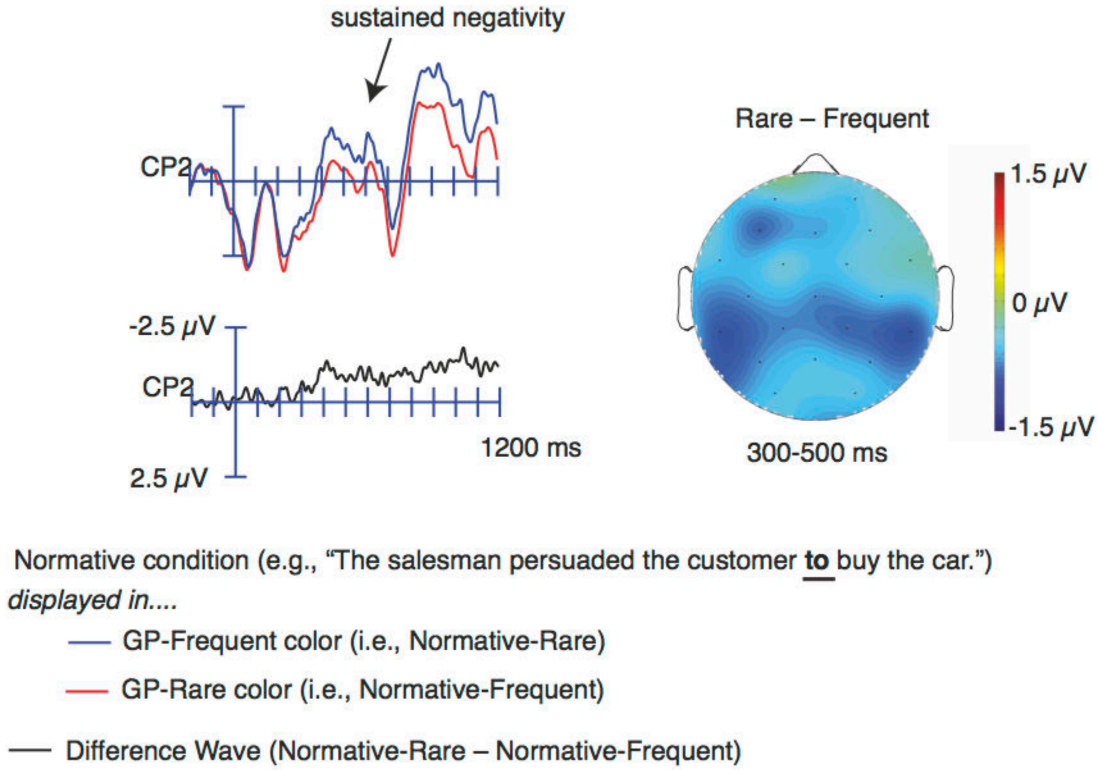

Figure 6.

ERPs to the infinitival marker *to* in Normative sentences presented in the GP-Frequent versus GP-Rare color. Similar to the effect shown in Figure 5, a sustained negativity was observed to Normative sentences presented in the rare color relative to those presented in the frequent color.

Table 1

Example Sentences

Condition	Sentence Type	Example
Critical	GP	The salesman persuaded *to* conceal the sale *was* sent to jail.
	Normative	The salesman persuaded the customer *to* buy the car.
Violations	GP-Lure	*The salesman hoped to make the sale *was* given a raise.
	Salient	*The salesman drove the customer to the bank was given a raise.
Control		The salesman agreed *to* conceal the sale from the authorities.

Sentences shown above are designed for direct comparison and are not the actual sentences used in the study. The color manipulation was applied to sentences in the critical condition, such that 75% of GP sentences and 25% of Normative sentences were shown in color A (i.e., “GP-Frequent color”), while 25% of GP sentences and 75% of Normative sentences were shown in color B (i.e., “GP-Rare color”). Critical words are shown in italics.

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Table 2

Number of Trials Per Condition

Condition	Sentence Type	Number of Trials
Critical	GP, presented in GP-Frequent color	180 (4802)
	GP, presented in GP-Rare color	60 (1584)
	Normative, presented in GP-Frequent color	60 (1585)
	Normative, presented in GP-Rare color	180 (4683)
Violations	GP-Lure	40 (874)
	Salient	40 (992)
Control		40 (1067)

The first number indicates the number of trials in each condition prior to removing artifact and error trials, per participant. The second number in brackets indicates the final number of trials used in EEG analyses (combined across all 32 participants), after removal of artifact and error trials. Violation and Control sentences were presented in the two colors in equal proportions.