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Evidence for Priming Across Intervening Sentences During On-Line Sentence Comprehension

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Abstract

Three experiments investigated factors contributing to syntactic priming during on-line comprehension. In all of the experiments, a prime sentence containing a reduced relative clause was presented prior to a target sentence that contained the same structure. Previous studies have shown that people respond more quickly when a syntactically related prime sentence immediately precedes a target. In the current study, ERP and eyetracking measures were used to assess whether priming in sentence comprehension persists when one or more unrelated filler sentences appear between the prime and the target. In experiment 1, a reduced P600 was found to target sentences both when there were no intervening unrelated fillers, and when there was one unrelated filler between the prime and the target. Thus, processing the prime sentence facilitated processing of the syntactic form of the target sentence. Experiments 2 and 3, eye-tracking experiments, showed that target sentence processing was facilitated when three filler sentences intervened between the prime and the target. These experiments show that priming effects in comprehension can be observed when unrelated material appears after a prime sentence and before the target. We interpret the results with respect to residual activation and implicit learning accounts of priming.

Keywords

syntax; priming; sentence processing; syntactic priming

“The nature of the mechanism behind structural priming deserves more attention.”

--Kay Bock and Zenzi Griffin

This article focuses on the nature of the mechanism behind *structural priming*. Structural priming, also known as *syntactic priming* or *structural persistence*, describes the outcome when exposure to one sentence influences the processing of a subsequent sentence that shares aspects of grammatical form (or syntactic structure; Bock, 1986; Hartsuiker & Kolk, 1998; Pickering & Branigan, 1998; Pickering & Traxler, 2004; Tooley et al., 2009; Traxler, 2008a, b; Traxler & Pickering, 2005). As Bock and colleagues, (2007, p. 439), note, “Structural persistence is a tendency to echo syntactic structures from recent experience, despite changes in the meaning, in the wording, (or) even in the language embodying the persistent structure.”

Syntactic priming effects have been observed in both production and comprehension. In production, exposure to a prime sentence of a given syntactic type leads speakers to use that

type with greater frequency in the future (Bock, 1986; Hartsuiker et al., 2008; Pickering & Branigan, 1998). In experiments involving picture description, for example, hearing or reading a passive-voice sentence (*The church was struck by lightning*) makes it more likely that a participant will produce a passive-voice form to describe an unrelated picture (compared to trials on which the participant had heard an active voice sentence). Hearing an active-voice sentence (*Lightning struck the church*) makes it less likely that a passive-voice sentence will be forthcoming.¹ In comprehension, the influence of exposure to a prime sentence can be seen in the processing and final interpretation of a subsequent sentence. Such influences can be seen during on-line construction of an interpretation using methods such as eye-tracking during reading, visual-world eye-tracking, and ERPs (Arai et al., 2007; Ledoux et al., 2007; Thothathiri & Snedeker, 2008a, b; Tooley et al., 2009; Traxler & Tooley, 2008). In behavior, exposure to a syntactically related prime sentence leads to faster reading of a target sentence, usually at or shortly after comprehenders encounter a syntactic choice point. In ERPs, similar exposure results in a reduced positivity at and following syntactically disambiguating words in target sentences. Exposure to prime sentences also influences the final outcome of the interpretation process in globally ambiguous sentences (Branigan, Pickering, & McLean, 2005).

In comprehension priming experiments, speeded processing of target sentences or modulations of ERPs could reflect processing of various kinds, lexical, semantic, referential, or syntactic, among others. Previous studies have therefore attempted to localize the source of observed priming effects. These studies indicate that syntactic processes contribute substantially to observed priming effects, with semantic overlap playing a weaker role that is localized differently than the syntactic effects in these experiments (see Tooley & Traxler, 2010, for a review). Different sentence types may be differentially affected by factors such as lexical overlap between prime and target sentences (Pickering et al., 2012; Traxler, 2008a; Sturt, et al., 2010), and some facilitatory effects may be related to lexical repetition or semantic processes, but the weight of evidence suggests that syntactic processes, including re-parsing, contribute to the observed effects.

Evidence for syntactic contributions to facilitatory effects can be found in both reading time and ERP outcomes. For example, prime sentences that have the same overall abstract structure, such as (2) and (3), but not completely parallel structure at a more local level will facilitate processing of target sentences such as (1) (Pickering et al., 2011; Pickering & Traxler, 2004; Traxler, 2008; Traxler & Pickering, 2005; Traxler & Tooley, 2008):

- (1) The defendant examined by the lawyer turned out to be unreliable.
- (2) The engineer who was examined by the board passed with flying colors.
- (3) The engineer who was examined passed with flying colors.

In eye-tracking experiments, these facilitated processing effects are consistently localized to the syntactically disambiguating by-phrase (*by the lawyer* in 1), although repetition priming effects at the verb (e.g., *examined*) also occur in some experiments. In ERP experiments, facilitated syntactic processing following prime sentences like (4) results in reduced positivities during processing of syntactically disambiguating by-phrase (*by the board, by the lawyer*) words in target sentences, such as (1) (Ledoux et al., 2007; Tooley et al., 2009):

- (4) The engineer examined by the board passed with flying colors.

Note that priming effects for reduced-relatives have previously been observed only when the same verb appears in both the prime and target sentence.

¹Recent experiments provide evidence that exposure to a given syntactic form may have separable influence on the likelihood of selection and the timing of planning processes during speech production (Segaert et al., 2011a, b)

Reduced positivities in sentence processing studies are typically referred to as the P600 effect. P600 modulations were first observed in experiments that exclusively assessed syntactic manipulations (e.g., violations of agreement and word order, syntactic ambiguity, and syntactic complexity (see Kutas et al., 2006, for a review). More recently, P600 effects have also been observed when syntactic information conflicts with semantic information in the sentence (e.g., thematic violations in syntactically unambiguous sentences; Kim & Osterhout, 2005; Kuperberg et al., 2006; Nakano, Saron & Swaab, 2010). Importantly, many ERP studies have shown P600 effects indicating syntactic processing difficulties in syntactically ambiguous sentences such as those tested here.

Further, facilitated processing of syntactically disambiguating material in sentences like (1) is not observed when the verb in the prime sentence is only semantically related to the verb in the target. In Tooley and colleagues' (2009) study, sentences like (5) did not facilitate processing of targets like (1):

- (5) The engineer inspected by the board passed with flying colors.

In addition, in Traxler and Tooley's (2008) study, establishing a semantic relationship between prime and target sentences by repeating a subject noun led to repetition priming of the subject noun, but no priming effects occurred during processing of the syntactically disambiguating by-phrase.

Finally, in experiments involving modifier-goal ambiguities, such as (6), syntactically disambiguating parts of target sentences were processed more rapidly than normal even when the prime sentence (e.g., 7) was semantically unrelated to the target:

- (6) The girl dropped the blanket on the floor on the bed this morning.

- (7) The historian read the letter to the Romans to the class last week.

These results suggest that priming effects observed at and following syntactically disambiguating material in comprehension (especially in reduced relatives, which have received the most attention to date), are driven by syntactic representations and processes, as opposed to purely semantic or lexical ones. This is not to say that semantic processes could not facilitate processing of by-phrases in such sentences, but rather that in the paradigm used in the current study, syntactic processes are the most likely source of the priming effects.

Syntactic priming occurs in both production and comprehension, but discussion continues as to the precise mechanisms and processes that give rise to such effects. Identifying the mechanisms and processes that trigger syntactic priming in comprehension could help us better understand how lexical and syntactic representations are organized. It could also help us understand how comprehension processes compare to production processes. We return to these issues in the General Discussion.

How Persistent is Syntactic Priming in Comprehension?

The three experiments reported here were designed to test whether syntactic priming of reduced relative clauses can be observed when one or more unrelated sentences appears between the prime sentence and the target. To date, syntactic priming that persists across unrelated intervening sentences has been commonly observed in production (Bock & Griffin, 2000; Hartsuiker et al., 2008), whether or not specific lexical items appear in both the prime and target utterances. Much less is known about the existence and nature of similar effects in on-line comprehension. However, recent studies have shown that repeated exposure to a given sentence type can have long-lasting facilitative effects (Long & Prat, 2008; Tooley, 2009; Wells et al., 2009). In addition, preliminary data from the visual world paradigm indicate that a prime sentence may affect processing of a target sentence when a

single unrelated sentence intervenes between the prime and target (Carminati & van Gompel, 2009). Finally, in two ERP studies, syntactic priming effects, as indicated by modulation of the amplitude of the P600, were observed when a comprehension question intervened between the prime and the target sentence (Ledoux et al., 2007; Tooley et al., 2009).

Finding out what happens when unrelated sentences intervene between a prime and a target can help constrain accounts of syntactic priming in comprehension, as it has done in production. Although we have data from massed exposure studies (Long & Prat, 2008; Wells et al., 2009), we do not know what happens in comprehension under conditions that more closely resemble typical production priming experiments. If priming effects in comprehension do not survive at lags greater than zero, this would suggest a qualitative difference between production and comprehension in terms of the mechanisms and processes that produce priming.

Therefore, the main goal of this study was to determine what happens during sentence comprehension when unrelated sentences appear between a prime sentence and a target sentence. We used both event-related potential (ERP) and behavioral (eye-tracking) methods to assess comprehenders' response to sentences containing *reduced relative* clauses, such as sentence (1):

(1) The defendant examined by the lawyer turned out to be unreliable. Such sentences have been shown to produce highly robust syntactic priming effects during on-line comprehension in *lag-zero* experiments (that is, experiments in which the target sentence immediately follows the prime sentence; Tooley et al., 2009; Traxler & Tooley, 2008). In eye-tracking, priming effects are observable as reduced fixation times on the syntactically disambiguating by-phrase region [*by the lawyer* in (1)], and reduced total reading times on the verb region that precedes the by-phrase region [*examined* in (1)]. In ERP experiments, reductions in syntactic processing difficulty in the target sentence manifest as reductions in the P600 to critical disambiguating words that follow a repeated verb in the target sentence, when the electrophysiological response to the target sentence is compared to the electrophysiological response to the prime sentence. Presumably, these P600 effects reflect the difficulty incorporating the syntactic form of the by-phrase with the preceding context. Standard processing accounts suggest that readers anticipate a noun-phrase (as in *The defendant examined the evidence*) rather than a prepositional-phrase/reduced relative clause modifier. The clash between the likely or syntactically simpler anticipated outcome and the actual outcome initiates syntactic repair processes, giving rise to the P600. Reductions in the N400 at the repeated verb have also been observed, but contrast in polarity with effects at and following syntactic disambiguation.

Experiment 1: ERPs at Lag 1

The first experiment investigated how the presence of a prime sentence influenced the neurophysiological response to a target sentence that had the same syntactic form. Consistent with prior ERP studies of syntactic priming in comprehension, we tested participants' response to reduced-relative sentences, such as (1) above (Ledoux et al., 2007; Tooley et al., 2009). Participants' responses were assessed in two different conditions. The first condition, the *lag zero condition*, closely resembled the procedures used in the previous ERP studies, in that the prime and target sentences were immediately adjacent. In the other condition, the *lag one condition*, one unrelated filler sentence intervened between the prime sentence and the target. By measuring ERPs to the critical verb and the disambiguating words following the verb in the prime and target sentences, we could assess how processing the prime sentence affected the neurophysiological response to a subsequent target sentence.

If processing the prime sentence facilitates syntactic structure-building processes in the target, we should observe a reduced P600 to the disambiguating words that follow the repeated verb in the the targets, compared to the primes.

Method

Participants—Sixteen undergraduates from the University of California, Davis gave informed consent and took part in the study and were compensated with course credit. All were right-handed, native speakers of English, with no reported hearing loss or psychiatric/neurological disorders.

Stimuli—The experimental items were 160 reduced relative clause sentences, comprising 80 prime-target pairs. Prime sentences were either directly followed by target sentences (lag zero condition), or else primes and targets were separated by one intervening filler sentence (lag 1 condition). All prime-target sentence pairs contained the same verb:

(Prime) The defendant examined by the lawyer turned out to be unreliable.

(Only Lag1: Filler) The tour guide led the people around the museum slowly.

(Target) The engineer examined by the board passed with flying colors.

Primes and targets were counterbalanced across four lists, such that each prime sentence in one list served as a target sentence in another list. Versions of items were assigned to one of four lists using a Latin-square design. The items were presented to participants in a fixed, randomized order (so that all participants went through a given list of items in the same order). In addition, prime-target pairs presented with no intervening sentence in one list were presented with an intervening sentence in another list. For example, the sample prime listed above would serve as a prime in the lag zero condition in one list, as a prime in the lag one condition in another list, as a target in the lag zero condition in the third list, and finally as a target in the lag one condition in the last list. Each participant was tested on one of the four lists, with equal numbers of participants tested in each. Importantly, this counterbalancing permitted the comparison across prime and target items of the exact same sentences, thereby controlling for any possible differences in length or frequency between individual items.

In addition to the experimental items, there were 125 filler sentences, 40 of which served as intervening sentences for lag one condition prime-target pairs.ⁱⁱ Each block began with a filler sentence so that muscle-movement artifacts that often occur early in the block (as the participant settles in) would not impact experiment items. The filler sentences were of variable syntactic structure, and contained a mixture of sentence types and subject matter. For example, some filler sentences had a main clause structure (The professor finished his lecture five minutes early), while others contained relative clauses (The drummer that criticized the guitarist quit the band). Some fillers contained prepositional phrases (The family decorated the tree with silver and gold ornaments). No verbs used in the filler items were repeated in the prime-target pairs. We assumed, on the basis of prior results (Tooley et al., 2009, 2012; Traxler & Tooley, 2008), that prime sentences themselves would not be primed by exposure to prior sentences containing reduced relatives. This assumption was based on the absence of priming at lag 0 when reduced-relative prime and target sentences did not have the same verb.

ⁱⁱThe full list of items for this experiment, as well as Experiments 2 and 3, is available upon request from the senior author, mjtraxler@ucdavis.edu

Procedure

Participants were tested in a comfortable chair in an electrically shielded, sound-attenuating booth. The sentences were presented one word at the time using Presentation software, and participants were instructed to read the sentences and to respond after each trial with a button press, either to advance to the next sentence or to indicate true or false in response to a comprehension question. Twenty-five comprehension questions were included per list. The true or false questions did not follow prime sentences or, in the case of the lag one condition, filler sentences that appeared between prime-target pairs. Participants did not receive feedback on their responses. Trials began with a white fixation cross appearing for 1000 ms against a black background in the center of a computer screen approximately 100 cm in front of the subjects. The fixation cross was replaced by the first word of the sentence; all sentences were presented at a rapid serial visual presentation rate of 300 ms per word, with a 200 ms inter-stimulus interval. White horizontal bars appeared above and below words as a fixation aid. Five-hundred milliseconds following the offset of the final word, which was presented with a period, either the sentence “Press for next” or a true or false comprehension question appeared all at once on the screen. Participants responded using a keypad, with accuracy ranging from 80- 100%, averaging 90.5% across all participants. Each of the four lists was broken into nine blocks for presentation, each containing approximately 32 sentences.

Participants were asked to keep their eyes fixated on the center of the screen and to refrain from blinking or moving when the fixation cross was visible and during the presentation of the sentences. This was done to minimize subject-generated artifacts in the EEG signal. Subjects were told that they could blink and move their eyes when the “Press for next” or comprehension questions were on the screen. Stimulus codes specific to each condition were sent at the onset of the critical words in the sentence and these codes were used for later off-line averaging of the EEG.

ERP recording and data reduction—EEG was recorded from 29 tin electrodes, mounted in an elastic cap (ElectroCap International); additional electrodes were placed on the outer canthi and below the left eye in order to monitor eye movements and blinks. The outer canthi electrodes were referenced to each other, and the electrode under the left eye was referenced to channel FP1 (above the left eye) in the electrode cap. The right mastoid electrode was used as the recording reference for all EEG electrodes and the left mastoid. The left mastoid was recorded for later off-line algebraic re-referencing. The EEG signal was amplified with band pass cutoffs at .01 and 30 Hz, and digitized on-line at a sampling rate of 250 Hz (Neuroscan Synamp I). EEG was digitized continuously along with accompanying stimulus codes used for subsequent averaging. Impedances were kept below 5 k Ω .

Prior to off-line averaging, all single-trial waveforms were screened for amplifier blocking, muscle artifacts, horizontal eye movements and blinks over epochs of 1600 ms, starting 200 ms before the onset of the critical target words. Averaged ERPs were computed over artifact-free trials and were filtered off-line with a Gaussian low-pass filter with a 25 Hz half-amplitude cutoff. Statistical analyses were conducted on the filtered data.

We report results for four words, the reduced-relative verb (e.g., *examined* in 1), and the following three words, *by*, *determiner*, and *noun* (e.g., *by the lawyer* in 1).

Results and Discussion

Figure 1 shows the N400 effect of repetition at the verb for both the lag zero and the lag one conditions (e.g., *examined* in *The defendant examined by...*). Figure 2 shows the comparison

of the waveforms to the word *by* in the lag zero and lag one conditions (e.g., *by*, in *The defendant examined by...*). Figure 3 shows the priming effects at the determiner and noun for both the lag zero and lag one conditions (e.g., *the lawyer* in *...defendant examined by the lawyer...*). The baselines used to create the figures were identical to those used for the statistical analysis described below.

Analyses were conducted on the mean amplitude of the verbs and the critical words of the by-phrase (*by*, determiner, noun) that followed the verbs in the prime and target sentences. Separate analyses were conducted in epochs corresponding to the 300–500 ms (N400) and 500–800 ms (P600) time windows following critical word onset. In order to avoid distortion of the effects due to baseline differences between conditions coming from effects at the verb, the analysis for the critical word *by* was conducted time-locked to the verb, using a pre-verb baseline. Therefore, the N400 (300–500ms after verb) and P600 (500–800ms after verb) time windows for *by* corresponded to the 800–1000ms and 1000–1300ms epochs when time-locked to the verb. Likewise, in order to account for baseline distortion coming from effects at the word *by*, analyses for the determiner and noun in the by-phrase were conducted time-locked to *by*, using a pre-*by* baseline. Therefore, the N400 (300–500ms after determiner/noun) and P600 (500–800ms after determiner/noun) time windows for the determiner correspond to the 800–1000ms and 1000–1300ms epochs when time-locked to *by*, and for the 1300–1500ms and 1500ms–1800ms epochs for the noun when time-locked to *by*¹.

Repeated measures ANOVAs were performed with Lag (lag zero, lag one), Type (Prime, Target), and Electrode site (26 sites) as within-subjects factors. Additional ANOVAs over a subset of 11 central-posterior electrodes (C3, C4, CP1, CP2, CP5, CP6, P3, P4, CZ, PZ, POZ) where the N400 and P600 are typically maximal were conducted with the same factors. The Greenhouse-Geisser correction was applied to *F* tests with more than one degree of freedom in the numerator for all relevant analyses reported in this paper. ANOVA tables for the main effects and interactions of sentence type (prime vs. target), results described below are summarized in Table 1.

Verb Results—A main effect of Type was found in the N400 window to the verb ($F(1,15)=5.43$; $p=0.034$), such that waveforms to target verbs were reduced in amplitude (less negative) compared to prime verbs. No effect of Lag was found ($F<1$), nor were any interactions significant ($F_s<1.4$). No P600 effects were obtained to the verb ($F_s<2$).

By Results—No effects of either Lag or Type were found in either the N400 window ($F_s<1.7$), or in the P600 window ($F_s<1.9$) to the word *by*.

Determiner Results—A main effect of Type was found for the determiner in the N400 time window ($F=16.63$; $p=0.001$), such that waveforms to determiners in the prime sentences were more positive than those in target sentences. This effect of Type also interacted with Electrode ($F=4.23$; $p=0.0042$). No effects of Lag or any interactions with Lag were significant at the determiner ($F_s<1$) in the N400 time window. Similarly, a main effect of Type was found for the determiner in the P600 window ($F=9.53$; $p=0.007$), such that determiners in the prime conditions were more positively deflected than those in the

¹In order to address whether baseline differences could have contributed to the pattern of results reported here, we conducted additional analyses for the determiner, using a pre-verb baseline instead of a pre-*by* baseline. The use of a pre-verb baseline for all critical words required extracting EEG epochs extending beyond 2300ms in length, which resulted in a large amount of rejected trials due to the presence of artifacts (epochs over 1000ms are atypical, due to signal drift and participant movement). For this reason, it was impossible to analyze effects at the noun using a pre-verb baseline. However, the results for the determiner using a pre-verb baseline were consistent with those reported below, which used a pre-*by* baseline. This suggests that the current pattern of results cannot be attributed to the choice of baseline.

target conditions. As in the earlier window, this effect of Type also interacted with Electrode site ($F=4.32$; $p=0.0018$), and no effects of Lag or interaction with Lag were obtained ($F_s<1$).

Noun Results—A trend towards a main effect of Type was found for the noun in the N400 time window ($F=3.93$; $p=0.066$), such that waveforms to nouns in the prime sentences were more positive than those in target sentences. The effect of Type significantly interacted with Electrode ($F=4.3$; $p=0.0008$). No effects of Lag or any interactions with Lag were significant at the noun ($F_s<1$) in the N400 time window. Similarly, a main effect of Type was found for the determiner in the P600 window ($F=7.12$; $p=0.018$), such that determiners in the prime conditions were more positively deflected than those in the target conditions. As in the earlier window, this effect of Type also interacted with Electrode site ($F=2.8$; $p=0.02$), and no effects of Lag or interaction with Lag were obtained ($F_s<1$).

Central-Posterior Electrode Site Results—The subset analyses over 11 central-posterior electrode sites revealed the same pattern of results to those described above. An N400 effect of repetition priming was found at the verb ($F=8.8$; $p=0.009$), but again there was no effect of Lag ($F_s<1.4$). Significant effects of syntactic priming were found to the determiner in both the early ($F=20.74$; $p=0.0004$) and late time windows ($F=10.92$; $p=0.0048$), these effects also interacted with electrode ($F=4.1$; $p=0.0055$; $F=5.15$; $p=0.0014$); there was no effect of Lag in either time window ($F_s<1$). Finally, there was again a main effect of syntactic priming at the noun in both the early ($F=5.37$; $p=0.035$) and late ($F=8.85$; $p=0.0094$) time windows, which interacted with electrode ($F=4.09$; $p=0.0117$; $F=3.18$; $p=0.0328$). There was additionally a Lag $\times$ Electrode interaction in the N400 time window at the noun ($F=3.48$; $p=0.023$).

Simple Effects Analysis: In order to examine the effects of priming for each lag condition, repeated measures ANOVAs were performed with Type (Prime, Target), and Electrode site (26 sites) as within-subjects factors, separately for each Lag condition.

Lag Zero Verb Results: The effect of Type did not reach significance at the verb in either the N400 or P600 time windows at lag zero, nor did it interact with electrode ($F_s<1$).

Lag Zero By Results: The effect of Type did not reach significance at the verb in either the N400 or P600 time windows at lag zero, nor did it interact with electrode ($F_s<1$).

Lag Zero Determiner Results: A main effect of Type was found for the determiner in the N400 time window ($F=7.13$; $p=0.0175$). This effect of Type marginally interacted with Electrode ($F=2.54$; $p=0.0668$). Similarly, a main effect of Type was found for the determiner in the P600 window ($F=6.72$; $p=0.0204$), which did not interact with electrode site ($F<2.04$).

Lag Zero Noun Results: The main effect of Type did not emerge as significant at the noun in the N400 time window, nor did it interact with electrode in this time window ($F_s<2.44$). The effect of Type was significant in the P600 time window ($F=4.73$; $p=0.0461$), and did not interact with electrode ($F<1.4$).

Lag One Verb Results: A main effect of Type was found in the N400 window to the verb ($F=6.41$; $p=0.0231$), such that waveforms to target verbs were reduced in amplitude (less negative) compared to prime verbs. This effect of Type did not interact with electrode ($F<1.5$). No P600 effects were obtained to the verb ($F_s<1$).

Lag One By Results: No effects of Type were found in either the N400 window ($F_s < 1$), or in the P600 window ($F_s < 1$) to the word *by*.

Lag One Determiner Results: A main effect of Type was found for the determiner in the N400 time window ($F = 7.15$; $p = 0.0173$), such that waveforms to determiners in the prime sentences were more positive than those in target sentences. This effect of Type did not interact with Electrode ($F < 1.7$). A main effect of Type was also found for the determiner in the P600 window ($F = 6.51$; $p = 0.0222$), such that determiners in the prime conditions were more positively deflected than those in the target conditions. As in the earlier window, this effect of Type also interacted with Electrode site ($F = 2.5$; $p = 0.0379$).

Lag One Noun Results: No effects of Type were found in either the N400 window ($F_s < 2.08$), or in the P600 window ($F_s < 3$) to the noun.

Repetition of the verb in the target sentences led to a reduction of the N400 relative to the first presentation of the verb in the primes. The size of this effect did not differ as a function of the lag manipulation. This replicates findings of Ledoux et al. (2007), and Tooley et al. (2009).

Importantly, P600 effects were obtained across both lag conditions at the determiner and the noun of the critical *by*-phrase: Determiners and nouns in target sentences showed reduced P600 amplitudes compared to those observed in prime sentences. This effect was also significant in the N400 time window. However, this difference most likely reflects an early positive shift found for determiners and nouns in prime sentences compared to those in target sentences, rather than a canonical N400 effect. A larger negative shift for the determiners/nouns in prime sentences compared to targets would have been consistent with an N400 effect. However the current results show a larger positive shift for the prime sentences. Although this effect begins in the N400 time window, we interpret our results at the determiner as reflecting the beginning of an extended positivity (P600). The determiner comes at a point during the processing of the sentence that is one word after the reader has encountered the structural difficulty (i.e. just following *by*), and therefore it is not surprising that the onset of the effect at the determiner is relatively early for a P600.

In sum, the results indicate that processing of a reduced relative target sentence is affected by the presence of a reduced relative prime sentence. Reduced positivity following presentation of the determiner, whether the target sentence followed the prime immediately or followed one unrelated intervening sentence, provided the strongest indication of such an influence. The priming effect in the lag zero condition replicates similar effects in the two previous ERP studies of syntactic priming in comprehension for this sentence type (Ledoux et al., 2007; Tooley et al., 2009). The persistence of such effects in the lag one condition has not previously been observed, with the possible exception of Ledoux and colleagues' and Tooley and colleagues' experiments. In those ERP experiments, a comprehension question followed every sentence in the experiment. Thus, these experiments might be viewed as showing a priming effect at lag one as well. However, because the comprehension question always referred to the immediately preceding sentence, it may have served to preserve or refresh a trace of aspects of the prime sentence, including its syntactic form. This cannot explain the results of the present experiment, since an unrelated structure intervened between prime and target sentences in the lag 1 condition.

It is also worth noting that the P600 effect was found to different words in the disambiguating "by-phrase" that followed the repeated verb in Ledoux et al. (2007), Tooley et al (2009), and the present study. In Ledoux and colleagues' (2007) study, modulations of the ERP signal appeared to the noun within the by-phrase (e.g., *lawyer* in example 1). In

Tooley and colleagues' (2009) study, similar effects appeared to the preposition *by*, the earliest point at which syntactic disambiguation could occur. In the current experiment, the P600 effect was found to the determiner (*the*) in the *by* phrase, as well as the following noun. Given that the present experiment was designed to determine if syntactic priming effects survive the presentation of intervening sentences with a different structure, variability of the precise point in the sentence at which the modulation of the ERPs occurs is not of great significance. Variability in the precise timing of effects across three ERP experiments is comparable to the variability that has been observed in behavioral studies of this sentence type. In many of the eye-tracking studies that used this paradigm (e.g., Tooley et al., 2009, Experiment 2; Traxler & Tooley, 2008), effects emerge in first-pass reading time or first-pass regressions from within the *by*-phrase (*by the lawyer* in example 1). However, such effects sometimes emerge only in measures like total time, which can be affected by relatively “late”; interpretive events. Furthermore, the eye-tracking region of analysis includes the word *by*, the determiner, and the following noun, and so does not differentiate between the different effects on these three words. It is therefore possible that a more fine grained analysis of the eye-tracking data in the previously mentioned studies would reveal an analogous jittering in the exact timing of the effect. Future studies may identify what drives the exact onset of the syntactic priming effect.

For our purposes, the critical finding is that a reduced P600 was found to the determiner and following noun in the disambiguating *by* phrase of the target sentences compared to the determiner and following noun in the same region in the primes), and that the reduction in the P600 amplitude was about the same in the lag one trials as the lag zero trials. These outcomes suggest that the beneficial effects of processing the prime are not noticeably reduced by the presence of a single unrelated filler sentence. It could be the case that inserting the filler sentence delays the onset of the priming effect. This possibility seems less likely, however, because the timing of the priming effects appeared to be about the same in the current experiment in the lag zero and lag one trials. While we can not rule out all differences between processing of the target sentences between the lag zero and lag one conditions on the basis of this single set of results, the results do suggest that the broad outlines of the target-sentence response are similar in the lag zero and lag one conditions.

Experiment 2: Eye-Tracking at Lag 3

The ERP experiment provided evidence that syntactic priming effects during the comprehension of reduced relative target sentences are of similar magnitude whether prime and target sentences are immediately adjacent, or whether a single unrelated filler sentence separated the prime from the target. Our second experiment, which used eye-tracking rather than ERPs to assess readers' responses, was designed to further test whether priming effects in comprehension survive across unrelated material. This experiment also used reduced relatives as primes and targets. To test whether priming effects could survive at longer lags, primes and targets were separated by three unrelated sentences. This experiment has the potential to provide converging evidence for persistent syntactic priming in the comprehension of sentences containing reduced relative clauses.

Method

Participants—34 undergraduates from UC Davis participated to complete a course requirement.

Stimuli—There were 72 items like (1), repeated here:

- (1) The defendant examined by the lawyer turned out to be unreliable.

Each participant read a total of 72 sentences like (1), 36 as primes and 36 as targets.

Within each prime-target pair, the target was separated from the prime by three unrelated sentences. A trial thus consisted of presentation of a prime sentence, three unrelated filler sentences, and a target sentence. For example, a trial would appear like this (except each sentence was displayed on a computer screen by itself):

(Prime) The defendant examined by the lawyer turned out to be unreliable.

(Filler 1) The tour guide led the people around the museum slowly.

(Filler 2) The pastry chef invented a new kind of cookie dough.

(Filler 3) The dogs played together all day at the dog park.

(Target) The engineer examined by the board passed with flying colors.

By rotating items across lists, each prime sentence (on one list) served as a target sentence (on a different list). Thus, prime-target comparisons were made across the same sentences. This eliminates concerns about the length and frequency of the individual words as well as possible effects of additional ambiguities beyond the reduced relative-main clause ambiguity. The estimates of the priming effects were based on measuring readers' responses to sentences like The defendant examined by the lawyer proved to be unreliable when it appeared as a prime and when it appeared as a target. Three intervening filler sentences with an unrelated structure appeared between the prime and target sentences.

Counterbalancing of sentences across lists accomplished the following goals: 1) Every prime sentence (on one list) served as a target sentence (on a different list). 2) A participant read any particular sentence exactly once. After experimental sentences were randomly assigned to one of two lists, the experimental and filler sentences were presented to participants in a fixed order.

The experimental sentences were displayed along with 122 filler sentences of various types, most of them with simple transitive or intransitive constructions (for example, The player tossed the bat at the fence when he struck out). Thus, all of the fillers represented relatively commonly occurring sentence types with fairly straightforward syntactic properties. Some consisted of conjoined main clauses (The worker framed the house and supervised the sheet rock hangers). Some had verbs with infinitival complements (*The students wanted summer vacation to start*). Some of the fillers had prepositional phrase modifiers (The sister wore the dress with the big blue bow on the hip.) (All of the stimulus lists are available from the senior author upon request: mjtraxler@ucdavis.edu) At least one filler sentence intervened between each experimental trial. None of the filler items had verbs that were used in the prime-target pairs.

Eye-movement Monitoring Procedure—A Forward Technologies dual-Purkinje image eye-tracker monitored participants' eye movements while they read the sentences. The tracker has angular resolution of 10' of arc. The tracker monitored only the right eye's gaze location. A PC displayed sentence materials on a computer monitor seventy cm from participants' eyes. The participants' gaze location was sampled every millisecond and the PC software recorded the tracker's output to establish the sequence of eye fixations and their start and finish times. Before the experiment, the participant was seated at the eye tracker and positioned with a chin cup and head rests to minimize head movements, and then the tracker was aligned and calibrated. Participants were instructed to press a button as soon as they had finished reading each sentence. After 22 of the filler sentences, the participant responded to a comprehension question. Participants did not receive feedback on their responses. The average percent correct was 93.7 (standard deviation = 5.98%), with a minimum of 77% and a maximum of 100%. Between each trial, a pattern of squares appeared on the computer screen along with a cursor that indicated the participants' current

gaze location. If the tracker was out of alignment, it was recalibrated before proceeding with the next trial.

Analyses—Four standard eye-movement measures were computed for each participant: 1) *First-pass time* is the sum of all fixation durations beginning with the first fixation in a region until the reader's gaze leaves the region, left or right; 2) *First-pass regression* reflects eye-movements that cross a region's left-hand boundary immediately following a first-pass fixation; 3) *Regression-path time* includes all of the fixations from the first fixation in a scoring region until the reader fixates somewhere to the right of the scoring region (Konieczny et al., 1997; Traxler et al., 1997). This measure includes time spent re-fixating previous regions; 4) *Total time* is the sum of all fixation durations in a region, regardless of order.

Three scoring regions were analyzed. The *verb* region consisted of the verb inside the relative clause (e.g., *examined* in 1). The *PP* region consisted of the prepositional phrase (e.g., *by the lawyer*). The PP region was analyzed as a whole because it is a linguistically defined unit that has been used in previous priming studies using the eyetracker (e.g., Tooley et al., 2009; Traxler & Tooley, 2008), and previous studies involving the reduced relative sentence type that did not involve priming manipulations (e.g., Clifton, et al., 2003). In addition, as in prior eye-tracking studies on this sentence type, we analyzed a *post-PP region* that consisted of the two words immediately following the end of the PP region.

Prior to determining fixation durations, an automatic procedure incorporated fixations of less than 80 ms into the largest fixation within one character. In the next stage, the procedure eliminated all individual fixations greater than 1000 ms and less than 80 ms. Subsequently, first pass times and total times of less than 120 ms were excluded from the analyses. Further, first-pass or total times exceeding 2000 ms for a given scoring region were excluded.

The data were analyzed using *hierarchical linear modeling* (HLM; Raudenbusch & Bryk, 2002; Traxler et al., 2005). In the particular application used here, HLM functions very similarly to repeated measures ANOVA, the chief difference being the use of random slopes and intercepts for each individual unit of analysis (participants and items; for a fuller discussion of similarities and differences between ANOVA and HLM, see Blozis & Traxler, 2007). Reading times were modeled as a function of sentence characteristics (whether the sentence appeared in the list as a prime sentence or a target). Participants had up to 72 responses (36 prime-target pairs). Separate models were run for each dependent measure for each scoring region. At the first level of the model, outcomes (dependent measures) were considered a function of *condition* (prime vs. target). At the second level of the model, parameter slopes and error terms were allowed to vary freely between individuals. Finally, a second set of models was run in which RTs were considered as nested within items rather than participants.ⁱⁱⁱ

Results and Discussion

First pass, first-pass regressions, regression path time, and total time results for the verb and PP scoring regions are summarized in Table 3.

ⁱⁱⁱThe by-participants multi-level models were configured as follows:

Level 1: RT for person *i*, for item *j* = $B_{0i} + B_{1i}(\text{sentence type})_j + e_{ij}$

Level 2: $B_{0i} = \mu_0 + u_0$

$B_{1i} = \mu_1 + u_1$

For the by-items models, transpose person and item.

No statistically significant effects were observed in any scoring region in the first-pass, first-pass regressions, or regression-path time data. However, significant effects of condition (prime vs. target) were obtained, as follows:

Verb Region—Total time in the verb region was 19 ms shorter in the lag 3 targets than in the corresponding primes. This effect was significant by subjects [$t_1(33) = -2.48, p < .05$], but marginal by items [$t_2(71) = -1.75, .05 < p < .10$]. Priming effects in total time at the verb are not accompanied by effects in other measures (first-pass time, first-pass regressions, or regression-path time) that presumably reflect earlier processing events. Thus, in this experiment, as in most other eye-tracking experiments of this kind of sentence, priming effects did not begin to appear until after readers fixated the disambiguating PP region.

PP Region—Total time in the PP region was 32 ms shorter in the lag 3 targets than in the corresponding primes. This effect was significant by both participants and items [$t_1(33) = 2.90, p < .01$; $t_2(71) = 2.01, p < .05$].

Post-PP Region—Total time in the spillover region was 35 ms shorter in the lag 3 targets than in the primes. This effect was significant by both participants and items [$t_1(33) = 3.53, p < .005$; $t_2(71) = 2.58, p = .01$].

Supplemental Analyses—As noted above, we assume based on prior results that little or no priming occurs from one trial to the next. If processing a reduced-relative prime and target on one trial influences processing of the prime sentence on the following trial, these eye-tracking results may actually under-estimate the absolute magnitude of the priming effects. A correlation analysis revealed a non-significant negative correlation between serial position within the experiment and total reading time for the disambiguating region within the prime sentences ($r = -.12, NS$). This non-significant effect could relate to some small between-trial priming effect or overall facilitation of reduced relative clause processing, but it could just as well reflect adjustment to the eye-tracking procedure. In addition, an analysis of reading times for the disambiguating region of the prime and target sentences revealed no relationship between serial position within the experiment and the size of the priming effect ($r = .011, NS$). Hence, neither the baseline reading time nor the size of the priming effect was related to position within the experimental list of items.

These results indicate that exposure to a reduced relative prime sentence can facilitate processing of a reduced relative target sentence even when three unrelated filler sentences appear between the prime and the target. The eye-movement patterns suggest that the priming effects occur only after participants encounter the syntactically disambiguating by-phrase.

Experiment 3: Lag 3 with Main Clause Fillers

Experiments 1 and 2 indicated that priming effects in sentence comprehension can occur when the prime and target sentences are separated by up to three unrelated sentences. Experiment 3 was designed to test whether a filler sentence that had the same verb as the prime and target but a different syntactic structure would disrupt the priming effects. We therefore manipulated properties of the filler sentences. As in Experiment 2, three filler sentences intervened between reduced relative prime and target sentences. As in Experiment 2, the prime and target sentences shared a verb (because these are the conditions under which priming has been shown to occur for the reduced relative sentence type). However, unlike Experiment 2, in Experiment 3, the second of the three filler sentences had the same verb as the prime and target, but had a main clause structure, as in (8):

(8) The tourist examined the map before entering the museum.

In previous studies (at lag zero) sentences such as (8) have had no effect on the processing of reduced relative target sentences (Pickering & Traxler, 2004; Traxler & Pickering, 2005; Traxler & Tooley, 2008).

Predicting what effect this filler manipulation will have depends on assumptions about the nature of syntactic representations and assumptions about how those syntactic representations are deployed during on-line comprehension. We will return to this topic in greater detail in the General Discussion, but briefly: If syntactic structure representations are accessed via lexical entries (MacDonald et al., 1995; Boland & Blodgett, 2006; Vosse & Kempen, 2000; Pollard & Sag, 1994), and if the most recent experience with a lexical item exerts the greatest influence on syntactic processing, then the amount of priming that occurs in Experiment 3 should be substantially less than that observed in Experiment 2. In Experiment 3, at the point in time where readers encounter the target sentence, their most recent experience with the critical verb (e.g., *examined*) will involve a syntactic structure that is different than the structure required for the target sentence. If priming survives under these conditions, then some influence other than the most recent experience must be driving that effect. In prior experiments where a main clause prime sentence has immediately preceded a reduced relative target sentence, no priming effects have been observed. Thus, priming under these conditions would indicate that the less recent prime sentence is exerting a greater influence on processing than the more recent filler sentence.

Determining why a more distant prime sentence should have a greater influence than a more recent filler sentence again requires some assumptions about how priming works. One possibility, raised in previous studies, is that rarer syntactic structures respond differently to priming manipulations compared to more frequently occurring structures (Segaert, et al., 2011a, b). Some production priming studies find differential susceptibility to priming across alternating forms, and this may be related to their relative frequencies (Bock, 1986; Luka & Barsalou, 2005; Pickering et al., 2002). In this experiment, sentences with reduced relative clauses served as primes and targets, while “main clause” sentences (like 8) served as fillers. These forms differ greatly in their overall frequency, as main clause constructions appear far more often than reduced relatives. Undertaking the mental processes necessary to parse and interpret a reduced relative may, therefore, have a greater persistent effect on performance than processing a main clause sentence. If so, the main clause filler sentences will not disrupt the effects resulting from processing of the reduced relative prime sentence.

A trial in Experiment 3 consisted of a reduced relative prime sentence, a reduced relative target sentence, and three filler sentences. Two of the three filler sentences were identical to those used in Experiment 2. However, the second of the three fillers was changed so that it had the same verb as the prime and target sentences, but a main clause structure, rather than a reduced relative clause structure. A trial therefore consisted of the following five elements (with example sentences):

1. Prime Sentence: The defendant examined by the lawyer was convicted yesterday.
2. (Filler 1): The tour guide led the people around the museum slowly.
3. Filler 2 (Main Clause Filler): The cook examined the tomatoes before making the soup.
4. (Filler 3): The dogs played together all day at the dog park.
5. Target: The engineer examined by the board passed with flying colors.

Method

Participants—48 UC Davis undergraduates participated under the same terms as Experiment 2.

Stimuli—The prime and target stimuli were identical to Experiment 2. The second of the three filler sentences from that experiment were replaced by a sentence that had the same verb as the prime and target, but a main clause structure (as in 8, above).

Apparatus and Procedure—The eye-tracking and data analysis procedures were identical to Experiment 2.

Results and Discussion

Table 4 presents mean values for the four dependent measures by region (verb, PP, spillover) and condition (prime vs. target). 5.4% of the data were excluded from the analyses using the same criteria as Experiment 2. Participants averaged 95% correct on the comprehension questions (range 69%–100%).

Verb Region—No priming effect was observed in the first-pass, first-pass regressions, or regression-path time data from the verb region. However, total time was shorter in the targets than in the primes [403 vs. 426 ms; $t_1(47) = 2.82, p < .01$; $t_2(71) = 2.70, p < .01$]. These results closely resemble the results for the verb region from the preceding Experiment 2.

PP Region—Significant priming effects were observed in the PP region in first-pass time (590 vs. 633 ms) by participants [$t_1(47) = 2.13, p < .05$] but not by items [$t_2(71) = 0.76$, NS]. Fewer first-pass regressions occurred in the PP region in the target sentences than the primes [10.8% vs. 12.8%; $t_1(47) = 1.98, p < .05$; $t_2(71) = 1.93, p < .06$]. Like first-pass time, the regression path time data produced a significant priming effect in the by-participants analysis but not in the by-items analysis [578 vs. 618 ms; $t_1(47) = 3.50, p < .002$; $t_2(71) = 1.50, p = .14$]. Analysis of the total time data indicated significant priming in the pp region [$t_1(47) = 3.10, p < .01$; $t_2(71) = 1.98, p < .05$].

Post-PP Region—The only significant effect in the post-pp region appeared in the first-pass regressions data. There were fewer first-pass regressions from the post-pp region in the target sentences than in the primes [$t_1(47) = 1.97, p = .05$; $t_2(71) = 2.11, p < .05$].

Supplemental Analyses—As in Experiment 2, we conducted two correlational analyses to assess whether baseline reading time or the size of the priming effects changed across the course of the experiment. A correlation analysis revealed a non-significant negative correlation between serial position within the experiment and total reading time for the PP-region within the prime sentences ($r = -.07$, NS). In addition, an analysis of reading times for the PP-region of the prime and target sentences revealed no relationship between serial position within the experiment and the size of the priming effect ($r = -.12$, NS). Hence, as in Experiment 2, neither the baseline reading time nor the size of the priming effect was related to position within the experimental list of items.

Cross-Experiment Comparison—Each trial in Experiments 2 and 3 differed only in the content of the second of three filler sentences. In Experiment 2, the second filler was random. In Experiment 3, the second filler had the same verb as the target sentence and the prime, but a different syntactic structure. We performed a further set of analyses to assess the degree of similarity in the results of Experiments 2 and 3. To do so, we analyzed total

time data from the disambiguating by-phrase (the PP-region), the main locus of the priming effects. These data were subjected to multilevel models with Experiment (2 vs. 3), condition (prime vs. target), and their interaction as random factors. These analyses produced no main effect of Experiment ($t_s < 1$, NS), and no interaction of Experiment with condition ($t_s < 1$, NS). There was a main effect of condition [$t_1(81) = 3.25$, $p < .01$, standard error = 9.82; $t_2(71) = 2.92$, $p = .03$, standard error = 14.4]. Thus, the analyses did not reveal any substantial differences in the results across the two experiments.

Similar to Experiment 2, this experiment produced evidence for facilitated target processing occurring after participants had read three filler sentences, one of which shared a verb with the target but had a different syntactic structure. Previous studies have shown that the main clause filler, by itself, is ineffective at facilitating processing of reduced relative target sentences (Ledoux et al., 2007; Traxler & Tooley, 2008). Thus, priming effects at the target must have been driven by exposure to the prime.

General Discussion

In Experiment 1, ERPs were measured to critical words in temporarily ambiguous target sentences that were preceded by structurally identical prime sentences. The primes and targets were either immediately adjacent (lag zero condition) or separated by one unrelated filler sentence (lag one condition). Both in the lag zero and the lag 1 conditions, a modulation of the N400 was found to the repeated verb in the target relative to the prime sentences. This effect was of similar magnitude in both lag conditions and indicates facilitated processing as a function of lexical repetition. However, in the disambiguating “by”-phrase following the verb, facilitated processing in the target sentence was instead observed on the P600; a reduced P600 was found to the determiner in the target sentences, even when there was an intervening filler sentence with a different structure. This P600 effect also did not differ in size as a function of the lag manipulation. Finally, a reduction in the amplitude of the N400 was found to the noun in the by phrase following the verb in the target sentence in both lag zero and lag 1 conditions. The change in the nature of the electrophysiological signature of facilitated processing of the repeated verb (N400), the adjacent words that follow in the disambiguating region (P600), and the noun that follows the disambiguating region (N400) suggests that the nature of the facilitated processing in the target sentence changes as more information becomes available to the reader. The N400 modulation to the noun in the target sentence suggests that semantic integration processes after syntactic disambiguation are facilitated as well.

One potential problem with the ERP experiment is the fact that words were presented one at the time (to prevent eye-movement artifacts in the ERP signal), and at a fixed rate, which could interfere with natural reading processes. However, the results of the two eye-tracking experiments of the present study validate the ERP findings, since faster reading times (in the eye-tracking experiments) and modulations of the N400 and P600 occurred at similar positions in the sentences. This suggests that sub-optimal reading conditions did not alter the on-line reading process in a significant way. Thus, a reduction in the amplitude of the P600 to the determiner in the disambiguating by-phrase in the target sentences relative to the primes supports the conclusion that participants had less difficulty processing the reduced relative structure when it was preceded by the same syntactic structure. To our knowledge, this is the first demonstration of syntactic priming when target sentences follow primes after an unrelated filler sentence with a different structure.

The ERP experiment was followed by two related eye-tracking experiments. In both eye-tracking experiments, target sentences were separated from the primes by three filler sentences. In Experiment 2, none of the filler sentences repeated the verb, and the results

showed that total time in the verb, PP, and spillover scoring regions were shorter in the target sentences than in their corresponding prime sentences. These findings indicate that processing the prime sentence facilitated processing of the target, despite the presence of unrelated filler material.

In Experiment 3, the prime and target sentences were also separated by three filler sentences. However, in contrast to experiment 2, the second of the three fillers contained the same verb as the prime and target, but had a main clause structure, rather than a reduced relative. Despite this intervening main clause filler, the target sentence had shorter total time in the verb and PP scoring regions, as well as fewer first-pass regressions from the spillover region. Thus, the presence of a main clause filler with the same verb as the target did not eliminate the processing benefit resulting from exposure to the reduced relative prime sentence.

Before interpreting these results further, we must first address two recurring issues in syntactic priming studies, namely the potential influence of participant strategies and potential semantic influences on target processing.

It is possible that because of repeated exposure to sentences containing reduced relatives, or exposure to prime-target pairs that have the same verb, participants developed a strategy that allowed them to more rapidly interpret the target sentences. A number of empirical findings make this hypothesis less likely, however: 1. Syntactic priming effects in eye-tracking occur in the absence of reliable strategic cues (Pickering & Traxler, 2004; Traxler, 2008a; Traxler & Pickering, 2005). 2. Syntactic priming effects in eye-tracking experiments are as large on the first trial, and on the first pair of trials, as they are in the experiments as a whole (Tooley et al., 2009). Similarly, there was no relationship between serial order in the experiment and the magnitude of priming effects in the current Experiments 2 and 3. These two types of results show that strategic cues are not necessary for priming effects to occur. 3. Syntactic priming fails to occur in the presence of valid strategic cues (Tooley et al., 2009). For example, repeating the subject noun rather than the critical verb does not lead to facilitated processing of the disambiguating PP region. 4. Explicitly warning participants to anticipate the immediate arrival of a reduced relative clause does not lead to facilitated processing of the disambiguating PP region (Traxler & Tooley, 2008). These latter findings indicate that strategic cues are not sufficient for priming to occur. If strategic cues are neither necessary nor sufficient for syntactic priming to occur during on-line sentence comprehension, then the explanation for the observed priming effects must lie elsewhere.

In principle, facilitated processing of target sentences in this study could reflect speeded semantic processing (akin to the kinds of processes that cause the word *hat* to prime the word *glove* in word priming studies; Balota et al., 2006). This *semantic priming* hypothesis has been addressed empirically in previous articles (Ledoux et al., 2007; Traxler, 2008; Traxler & Tooley, 2008). Most recently, Tooley and colleagues (2009) showed that priming effects for reduced relatives occurred when verbs were repeated across primes and targets, but not when the verb in the prime sentence was a synonym of the verb in the target sentence, in both ERP and eye-tracking experiments. This experiment showed that, for reduced relatives at least, a semantic relationship between the prime and target is not sufficient for facilitated processing to occur. In Traxler & Tooley's (2008) article, semantic overlap between subject nouns produced repetition priming of the subject noun but no observable effects on processing of the relative clause. In the two published ERP experiments involving reduced relatives, decreased P600 amplitude (rather than N400-like effects) point towards syntactic, rather than semantic, effects. The P600 is very sensitive to syntactic ambiguity, and even though the P600 effect has also been found in processing situations where there is a thematic or selection-restriction violation ("...the eggs were

eating...”), this is not the case in the kinds of sentences that were tested here. Further, in experiments with repeated verbs, but without repeated structure (as in main clause primes), there is no evidence for facilitated processing, especially in the relative clause region (the PP-region) that is the locus of the effects obtained in the current and previous experiments. In addition, facilitated processing of the PP region of reduced relatives occurs when reduced-relative target sentences follow “full relatives” (The defendant who was examined by the lawyer...) and “short relatives” (The defendant who was examined was convicted...). These results indicate that the abstract relative clause structure, rather than semantic or function-word overlap, is capable of facilitating processing of reduced relative target sentences, suggesting again that the facilitatory behavioral effects and the ERP results observed with these types of structures are driven by syntactic rather than semantic processes.

So, while we can point to a substantial body of experimental evidence indicating that facilitated processing reflects syntactic rather than semantic processes, we know of no evidence that semantic overlap produces similar outcomes. In our view, this state of affairs lays the burden of proof on advocates of the semantic hypothesis.

Implicit Learning and Comprehension Priming

To be maximally parsimonious, an account of syntactic priming in comprehension should also accommodate a wide range of findings from production (such as the rapid extinction of the lexical boost; Hartsuiker et al., 2008). It is always possible that the details of processing during comprehension differ from production, due to differences in inputs and outputs, the kinds of goals comprehension and production systems pursue, and the time courses over which they operate. We will therefore attempt to articulate an account for comprehension priming, and consider it an added bonus if the account successfully accommodates the full range of production priming phenomena as well.

For comprehension priming, the two most salient outcomes that need explanation are the lag priming effects (Experiments 1–3 here) and the lexical boost (Arai et al., 2007; Carminati & van Gompel, 2009; Pickering & Traxler, 2004; Pickering et al., 2011; Tooley et al., 2009; Traxler & Tooley, 2008). The mere existence of priming across intervening material would appear to support some form of implicit learning during online sentence interpretation (Chang et al., 2000, 2006; Luka & Barsalou, 2005). That is, an account under which exposure to a reduced relative strengthens the structure building processes for that syntactic structure would predict that processing of subsequent sentences with the same form will be speeded, whether the target sentence appears immediately or after a delay. This, by itself, could account for relatively long-lived priming effects.

However, these lag effects might simply reflect the slow decay of activation within combinatorial nodes associated with lemma representations (Pickering et al., 2002). In the limit, slow decaying activation would be indistinguishable from implicit learning. However, we believe that residual activation amongst lemma-combinatorial node representations does not provide a satisfactory explanation for the outcome of the current Experiment 3. In Experiment 3, the nearest related stimulus to the target had a main clause, rather than a reduced relative structure. Residual activation from this sentence should have reduced the accessibility of the reduced relative syntactic form. Thus, the more distant related stimulus, the reduced relative prime, appeared to exert greater influence on target processing in the current Experiment 3 than the more recently encountered main clause filler. This outcome would seem to largely rule out residual activation, even slowly decaying residual activation, as the source of the observed priming effects.

However, not all of the present findings neatly align with an implicit learning mechanism. For example, if participants immediately strengthen the representation of the reduced relative syntactic form via exposure and implicit learning, one would expect faster processing of that form during the experiment with increased exposure. Hence, reading times for reduced-relative sentences towards the end of the experiment should have been faster than reading times at the beginning of the experiment. The correlational analyses did not detect significant reductions in overall processing time for reduced-relative sentences across the course of the experiment, so this prediction was not borne out.^{iv}

Further, other aspects of the current findings may provide support for the residual activation account. First, the absolute magnitude of the priming effects in the two eye-tracking experiments are about half as big as the priming effects that have been obtained on nearly identical stimuli in five previous eye-tracking experiments (Pickering et al., 2011; Traxler & Tooley, 2008; Tooley et al., 2009). In these previous eye-tracking studies, the average total time effect in the PP region was 86 msec, with a range of 46 to 130. Thus, it is possible that the syntactic priming effects that we obtained in the eye-tracking experiments at lag three are smaller than the syntactic priming effects that occurred when similar sentences were tested at lags of zero. If this were the case, the difference could be attributed to the decay of residual activation with lag (comparable to Hartsuiker et al.'s, 2008, production results). Further, the precise timing of the onset of effects may have differed between the current (lag 3) and previous (lag 0) studies. Previous eye-tracking studies have produced relatively early priming effects (as evidenced by reductions in first-pass times during processing of the PP region), while the current experiments showed effects only in total time. In addition, the P600 effects of syntactic priming have been found to different words in the critical disambiguating by-phrase following the repeated verb, also indicating that the time course of priming effects may vary. Perhaps residual activation is responsible for earlier appearance of priming effects in previous lag zero experiments.

Concluding that patterns of priming really differ between lags of zero, one, and three may be premature, however. We only have three estimates of priming effects across lags of one (from ERP) and three (from eye-tracking), and a maximum of seven estimates of zero-lag priming effects (2 ERP and 5 eye-tracking experiments, depending on how one views the two preceding ERP experiments; Ledoux et al., 2007; Tooley et al., 2009). It may be too early, therefore, to strongly conclude that priming effects are smaller at lags of one or three than they are at lag zero. But if they were, this would seem to indicate that residual activation plays a role over and above the influence of implicit learning in producing syntactic priming effects, at least at lags of zero. Minimally, we would need some principled explanation for why priming effects are bigger at lag zero than at greater lags.

Of course, the residual activation and implicit learning mechanisms need not be mutually exclusive. The existence of one need not rule out the possible existence of the other. In fact, some accounts of syntactic priming explicitly incorporate separate mechanisms to deal with different experimental phenomena (Chang et al., 2006; Hartsuiker et al., 2008). Tooley and colleagues incorporated this assumption into their *dual-mechanism account* of syntactic priming in comprehension (Tooley, 2009; Tooley & Traxler, 2010; see also Traxler & Tooley, 2008). Like Hartsuiker and colleagues' (2008) account, the dual mechanism account incorporates aspects of both the combinatorial node and implicit learning accounts. According to this account, exposure to a prime sentence temporarily boosts the activation of the relevant combinatorial nodes. The combinatorial node that encodes the actual syntactic

^{iv}One might argue that the implicit learning is for the connection between lexical entries and syntactic structures. If so, implicitly strengthening the connection between the verb "examined" and the reduced relative clause structure would not necessarily facilitate processing a sentence that contained a different verb.

relationships that underlie the sentence's final interpretation ends up with the highest degree of activation. When the input is parsed and the stimulus-appropriate combinatorial node has been selected, the connection between the lemma and the selected combinatorial node is strengthened.^v When a target sentence is encountered immediately following a prime sentence, syntactic priming effects reflect the temporary increased activation of the combinatorial nodes shared between the prime and target as well as changes in representational strength caused by implicit learning. If a target sentence follows a prime at some distance, because unrelated sentences intervene, priming effects can still be observed based on changes in the strength of the connection between a lemma and its corresponding combinatorial nodes as a function of implicit learning. In production, this means that the structure is more likely to be selected, or that production latencies will be reduced. In comprehension, this means that the relevant structure is more rapidly activated or constructed.

How might the dual-mechanism account be implemented? A distinction between short-lived residual activation and longer-lived implicit learning mechanisms may be rooted in different memory systems, as proposed by some language learning accounts (e.g., Ullman, 2001).^{vi} Another possibility is that implicit learning and residual activation apply to different components of the memory systems that encode lexical and syntactic structure knowledge.^{vii} Assume for the moment that word-related knowledge, including syntactic structure possibilities, is encoded in a distributed fashion. (Figure 4 shows lemma and syntactic structure knowledge as localist representations, but this is not necessary and, in fact, the dual mechanism account could work just as well with distributed lexical and syntactic representations.) Assume that the verb *examined* has associations with the structural possibilities labeled in the “Syntactic Structures” component of Figure 4. Comprehending a reduced relative clause involving the verb *examined* (*The defendant examined by the lawyer...*) would temporarily enhance the connection between the lemma representation and the reduced relative pattern within the syntactic structure representations. This enhanced connectivity could be short-lived. Implicit learning processes might simultaneously facilitate the procedures used to arrive at the reduced relative analysis within the syntactic representation system. This enhanced procedural facilitation could be longer lived. If so, the system could produce a short-lived lexical boost and a longer-lasting general syntactic priming effect. The degree to which lexically independent priming could occur would be influenced by the relative strength of the different syntactic structure representations. In the case of reduced relatives, they may be so dominated by other structural possibilities (transitive and passive, for example) that the combination of lexical boost and implicit learning may be required before a facilitated response (priming effect) can be observed when a single prime sentence precedes a target. Other structures, where the possibilities are more balanced, may be more amenable to lexically independent priming and may show different patterns of priming across intervening material. This is potentially rich ground for future empirical research and modeling.

One advantage that various dual mechanism accounts share is that they can deal with a broader range of phenomena than either residual activation or implicit learning can by themselves. For instance, Chang and colleagues (2006) note that their implicit learning model does not produce the lexical boost when it attempts to simulate certain production priming results, “The dual-path model...does not exhibit increased structural priming when there is lexical or morphological overlap...The lexical enhancement of priming from content

^vSegaert and colleagues, 2011a, have proposed a more detailed account under which specific combinatorial nodes are tied to specific lexical entries, but exposure to a given syntactic form affects all related combinatorial nodes.

^{vi}We thank an anonymous reviewer for introducing this as a possibility.

^{vii}We thank an anonymous reviewer for raising this issue.

words is the only significant deviation between the model and priming data that we know of (p. 256).” However, as noted above, implicit learning offers a plausible explanation for priming across intervening material where residual activation may not. Thus, even advocates of implicit learning accounts of production priming recognize a need for a lexically based mechanism to produce less durable priming effects. “...Lexical-structural interaction reflects short-term bindings that are not as durably represented in the production system.”

Open Questions and Future Directions—These experiments provided evidence that syntactic priming occurs when unrelated fillers appear between the prime and the target. Because all of the conditions here involved repeating a verb across the prime and the target, these experiments do not address the question whether such effects can occur when verbs are not repeated across the prime and the target sentence. To date, there is limited evidence for verb-independent priming in comprehension (Traxler, 2008a; Thothathiri & Snedker, 2008a, b). The evidence we have may indicate that lexically independent priming is more robust for some sentence types than others, that the number of prime sentences matters, or that the type of task is critical. An important next step in this line of research is to see whether the kinds of effects obtained here extend to other sentence types (such as dative alternations or other forms of ambiguity) and whether the effects can be observed when the prime and target sentences do not share verbs (or other kinds of lexical items). Further, it will be important to determine whether the position of the related filler sentence influences the magnitude of priming across lags.

A final major open question is the degree to which syntactic priming in comprehension relies on the same mechanism as syntactic priming in production. Lexically independent priming has been reported in comprehension (Thothathiri & Snedeker, 2008a, b; Traxler, 2008a), but appears to be more robust in production priming studies. Production studies have produced very long-lived priming effects, lasting as long as several days (Bock & Griffin, 2000; Kaschak & Borreggine, 2008). Evidence for persistent priming is more limited in comprehension, but massed-priming studies involving extensive exposure to specific sentence types in comprehension have shown evidence for long-term learning effects (Long & Prat, 2008; Wells et al., 2009). The lexical boost, enhancements in priming effects when specific words are repeated across primes and targets, also appears to occur in both production and comprehension. Thus, there appear to be substantial similarities in the way priming effects manifest across production and comprehension. Because syntactic priming studies in comprehension are still a relatively new field of inquiry, it remains to be seen whether irreconcilable differences will be established between the two modalities. If such differences are established, they may reflect the nature of the tasks. In production, priming is often measured as changes in the likelihood of a binary choice. In comprehension, the effects are typically graded and may differ both in terms of overall processing time and the onset of effects. Recently, studies of production priming have begun to focus more on time-course (latency) issues, but the overall focus is still on the outcome of some structural choice. The most conservative position at the moment appears to be that much more research is needed, especially on comprehension, before strong conclusions about the overlap of mechanisms between production and comprehension are justified.

Finally, these results, along with compatible results from massed priming experiments (e.g., Wells et al., 2009; Long & Prat, 2008; Luka & Barsalou, 2005) may have implications more generally for models of parsing. Constraint-based lexicalist accounts of parsing emphasize the role of experience in shaping the way comprehenders respond to input (e.g., MacDonald et al., 1994). Accounts of this type are fully consistent with changes in performance resulting from exposure to particular sentence types. While the mere existence of priming effects in comprehension does not, by itself, pose a major challenge for two-stage, heuristic-

driven parsing, the existence of relatively long-lived priming in comprehension suggests that aspects of syntactic processing may flexibly adapt to changes in the input.

Conclusions

The ERP findings of this study offer to our knowledge the first evidence that syntactic priming modulates the P600 when an unrelated sentence intervenes between a prime and target sentence. The eye-tracking data provide the first behavioral evidence for syntactic priming across lags of three during on-line comprehension, even when one of the intervening fillers repeats the verb of the prime sentence, but in a different sentence structure. This set of findings could help bring the literature on comprehension priming a step closer to the literature on production priming. Long-lived priming effects have been attested in the production literature for over a decade. However, there is almost no evidence for comparable effects in comprehension. This study begins to provide that evidence. Finally, while further research is required, we believe that an account of the current findings, as well as the broader syntactic priming literature, will require two mechanisms: a residual activation mechanism operating on combinatorial nodes (or some similar representational substrate) and an implicit learning mechanism that can produce long-lasting changes in the pattern of connections in the underlying system of syntactic representations (see also Hartsuiker, 2008).

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Repetition Effects at the Verb: Lag Zero Condition

Repetition Effects at the Verb: Lag 1 Condition

Figure 1.

ERP effects of verb repetition for prime target pairs in the zero lag (top) and lag 1 (bottom) conditions. Verbs in prime sentences appear in blue, and verbs in targets sentences appear in dashed red. Negative is plotted up. The N400 time window appears shaded in light green, while the P600 time window is shaded in darker green.

Priming Effects at *by* : Lag Zero Condition Priming Effects at *by* : Lag 1 Condition **Figure 2.**

Comparison of the critical word “by” in prime (blue) compared to target (dashed red) sentences, in the zero lag (top) and lag 1 (bottom) conditions. ERPs are time-locked to the preceding verb; the x-axis represents a 1400 ms epoch after stimulus onset. Onset of “by” is at 500 ms. Negative is plotted up. The N400 time window appears shaded in light green, while the P600 time window is shaded in darker green.

Priming Effects at the Determiner and Noun: Lag Zero Condition

Priming Effects at the Determiner and Noun: Lag 1 Condition

Figure 3.

Comparison of the determiner in prime (blue) compared to target (dashed red) sentences, in the zero lag (top) and lag 1 (bottom) conditions. ERPs are time-locked to the preceding word (“by”); the x-axis represents an 1800 ms epoch after stimulus onset. Onset of the determiner is at 500 ms; onset of the noun is at 1000ms. Negative is plotted up. The N400 time windows appear shaded in light green, while the P600 time windows are shaded in darker green.

Figure 4.
Lemma and Syntactic Structure Representations

Table 1

Experiment 1: Main effects of lag (lag zero vs. lag one), sentence type (prime vs. target), and interactions with electrode site for Experiment 1. The first row represents the N400 epoch (300–500 ms post-stimulus). The second row represents the P600 epoch (500–800 ms post-stimulus).

All-Electrode Results										
VERB										
Epoch	Lag	Type		L × T		L × E		T × E		L × T × E
	F	p	F	p	F	p	F	p	F	p
N400	<1	0.5	5.43	0.05	<1	0.4	1.34	0.3	<1	0.4
P600	1.73	0.2	<1	0.79	<1	1.0	<1	0.4	<1	0.5
									1.25	0.3

BY										
Epoch	Lag	Type		L × T		L × E		T × E		L × T × E
	F	p	F	p	F	p	F	p	F	p
N400	1.7	0.2	<1	0.8	<1	0.5	<1	0.5	<1	0.4
P600	<1	0.4	<1	0.6	<1	0.6	1.9	0.1	<1	0.7
									1.14	0.3

DETERMINER										
Epoch	Lag	Type		L × T		L × E		T × E		L × T × E
	F	p	F	p	F	p	F	p	F	p
N400	<1	0.4	16.6	0.001	<1	0.9	<1	0.8	4.23	0.01
P600	<1	0.6	9.53	0.01	<1	0.9	<1	0.6	4.32	0.01
									<1	0.9

NOUN										
Epoch	Lag	Type		L × T		L × E		T × E		L × T × E
	F	p	F	p	F	p	F	p	F	p
N400	3.21	0.09	4.06	0.06	<1	0.7	<1	0.8	2.86	0.05
P600	<1	0.75	<1	0.4	<1	0.7	<1	0.8	1.13	0.35
									<1	0.5

11-Electrode Subset Results										
VERB, SUBSET										
Epoch	Lag	Type	L × T	L × E	T × E	L × T × E				
	F	p	F	F	p	F	p	F	p	p
N400	<1	0.9	8.8	0.01	<1	0.4	1.42	0.3	1.21	0.3
P600	<1	0.4	<1	0.5	<1	1.0	<1	0.8	2.32	0.1
										1.45
										0.3

BY, SUBSET										
Epoch	Lag	Type	L × T	L × E	T × E	L × T × E				
	F	p	F	p	p	F	p	F	p	p
N400	1.46	0.3	<1	0.5	1.16	0.3	<1	0.7	1.3	0.3
P600	<1	0.5	<1	0.8	<1	0.7	<1	0.5	1.6	0.2
										1.6
										0.2

DETERMINER, SUBSET										
Epoch	Lag	Type	L × T	L × E	T × E	L × T × E				
	F	p	F	p	p	F	p	F	p	p
N400	<1	0.5	20.7	0.001	<1	0.8	<1	0.7	4.1	0.01
P600	<1	0.8	10.9	0.005	<1	0.8	<1	0.9	5.15	0.001
										<1
										0.9

NOUN, SUBSET										
Epoch	Lag	Type	L × T	L × E	T × E	L × T × E				
	F	p	F	p	p	F	p	F	p	p
N400	2.64	0.1	2.69	0.1	<1	0.7	<1	0.6	3.5	0.05
P600	<1	0.4	<1	0.5	<1	1.0	<1	0.8	1.6	0.2
										<1
										0.6

Note: For the main analyses, degrees of freedom for main effects are (1,15) and for interaction terms are (25,375). For the subset analyses, degrees of freedom for main effects are (1,15) and for interaction terms are (10,150). N400 refers to the 300–500 ms post-stimulus epoch. P600 refers to the 500–800 ms post-stimulus epoch. Statistically significant results appear in **bold**.

Table 2

Experiment 1: Simple effects comparisons, testing the effect of sentence type (prime vs. target), and interactions with electrode site for each lag condition in Experiment 1. The first row represents the N400 epoch (300–500 ms post-stimulus). The second row represents the P600 epoch (500–800 ms post-stimulus).

LAG ZERO: VERB				
Epoch	Type		T × E	
	F	p	F	p
N400	<1	0.35	<1	0.51
P600	<1	0.87	1.55	0.21

LAG ZERO: BY				
Epoch	Type		T × E	
	F	p	F	p
N400	<1	0.5	1.47	0.23
P600	<1	0.52	1.03	0.4

LAG ZERO: DETERMINER				
Epoch	Type		T × E	
	F	p	F	p
N400	7.13	0.02	2.54	0.07
P600	6.72	0.02	2.04	0.12

LAG ZERO: NOUN				
Epoch	Type		T × E	
	F	p	F	p
N400	2.44	0.14	1.96	0.13
P600	4.73	0.04	1.38	0.26

LAG ONE: VERB				
Epoch	Type		T × E	
	F	p	F	p
N400	6.41	0.02	1.47	0.24
P600	<1	0.86	<1	0.54

LAG ONE: BY				
Epoch	Type		T × E	
	F	p	F	p
N400	<1	0.64	<1	0.4
P600	<1	0.9	<1	0.59

LAG ONE: DETERMINER				
Epoch	Type		T × E	
	F	p	F	p
N400	7.15	0.02	1.7	0.16
P600	6.51	0.02	2.5	0.04

LAG ONE: NOUN				
Epoch	Type		T × E	
	F	p	F	p
N400	1.88	0.19	2.08	0.09
P600	2.95	0.11	1.5	0.2

Table 3

Experiment 2. Mean first-pass, first-pass regressions, regression-path time, and total reading time by scoring region and condition.

First Pass Time			
	Verb Region	PP Region	Spillover
Prime	329 (8.11)	512 (23.1)	418 (15.6)
Target	319 (5.08)	504 (8.6)	412 (12.4)
First Pass Regressions			
	Verb Region	PP Region	Spillover
Prime	9.95% (1.29)	13.0 (1.61)	12.9 (1.15)
Target	9.95% (1.29)	11.03 (1.37)	12.1 (1.16)
Regression Path Time			
	Verb Region	PP Region	Spillover
Prime	378 (11.9)	580 (24.1)	526 (19.0)
Target	370 (9.24)	565 (10.4)	527 (10.7)
Total Time			
	Verb Region	PP Region	Spillover
Prime	410 (11.7)	628 (25.6)	525 (20.4)
Target	391 (*) (7.7)	596* (11.2)	490** (9.81)

Note: Standard errors appear in parentheses.

* indicates the parameter differs from zero at $p < .05$ in both by-participants and by-items analyses

** indicates by-participants and by-items $p < .01$.

(*) indicates $.05 < p < .10$.

Table 4

Experiment 3. Mean first-pass, first-pass regressions, regression-path time, and total reading time by scoring region and condition.

First Pass Time			
	Verb Region	PP Region	Spillover
Prime	338 (8.49)	511 (17.9)	419 (13.1)
Target	331 (4.91)	493 (8.44)	418 (7.61)
First Pass Regressions			
	Verb Region	PP Region	Spillover
Prime	9.3% (1.00)	12.8 (1.42)	13.7 (1.19)
Target	8.0% (0.97)	10.8* (1.00)	11.5* (1.12)
Regression Path Time			
	Verb Region	PP Region	Spillover
Prime	403 (14.3)	618 (24.8)	486 (17.6)
Target	384 (9.86)	578 (11.5)	479 (11.8)
Total Time			
	Verb Region	PP Region	Spillover
Prime	426 (12.2)	633 (23.9)	514 (20.2)
Target	403** (8.29)	590* (13.9)	494 (10.2)

Note: Standard errors appear in parentheses.

* indicates the parameter differs from zero at $p < .05$ in both by-participants and by-items analyses

** indicates by-participants and by-items $p < .01$.

(*) indicates $.05 < p < .10$.