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Implicit learning of structure occurs in parallel with lexically-mediated syntactic priming effects in sentence comprehension

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Abstract

The aim of this study was to determine whether cumulative structural priming effects and trial-to-trial lexically-mediated priming effects are produced by the same mechanism in comprehension. Participants took part in a five-session eye tracking study where they read reduced-relative prime-target pairs with the same initial verb. Half of the verbs in these sentences were repeated across the five sessions and half were novel to each session. Total fixation times on the syntactically challenging parts of prime sentences decreased across sessions, suggesting participants implicitly learned the structure. Additional priming was also observed at the critical regions of the target sentences, and the magnitude of this effect did not change over the five sessions. These finding suggests long-lived adaptation to structure and short-lived lexically-mediated priming effects are caused by separate mechanisms in comprehension. A dual mechanism account of syntactic priming effects can best reconcile these results.

Keywords

Syntactic priming; comprehension; learning; lexical boost

Syntactic priming, or structural persistence, refers to the facilitated processing of grammatical structure due to some previously processed information or structure. The representational and processing systems that generate syntactic priming effects during language comprehension and production remain an active area of inquiry (see Pickering & Ferreira, 2008 and Tooley & Traxler, 2010 for reviews of language production and comprehension, respectively). Some accounts attribute syntactic priming effects to short-lived enhancement of activity in memory systems that connect abstract word-level representations (lemmas) to syntactic structure representations (Malhotra, Pickering, Branigan, & Bednar, 2008; Pickering & Branigan, 1998). Other accounts attribute syntactic priming effects to learning mechanisms that may underlie long-lived changes in patterns of production (Chang, Dell, & Bock, 2006; Reitter, Keller, & Moore, 2011). This study focuses

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on the representational systems and processes that produce syntactic priming effects in *comprehension*. Specifically, we test whether the mechanism that produces long-lived changes in comprehenders' responses to syntactic structure information is also responsible for structural facilitation driven by lexical and structural overlap.

Syntactic Priming in Production

Syntactic priming is quite robust in language production (Bock, 1986; Pickering & Branigan, 1998; Bock & Griffin, 2000; Cleland & Pickering, 2003 & 2006; and others), but has also been observed in several studies of language comprehension (Ledoux, Traxler, & Swaab, 2007; Pickering & Traxler, 2004; Traxler & Pickering, 2005; Arai, van Gompel, & Scheepers, 2007; Carminati et al., 2008; Thothathiri & Snedeker, 2008; Tooley, Traxler, & Swaab, 2009). Bock's (1986) original language production study asked participants to say sentences and then describe pictures of events, such as transfer events. Though the pictures could be described with either a double-object structure (e.g., "a rock star sold an undercover agent some cocaine") or prepositional object structure (e.g., "a rock star sold some cocaine to an undercover agent"), participants were more likely to use a structure, if they had just said a sentence with that particular structure. Importantly, this result was obtained when none of the content words were the same between the first sentence (the prime) and the sentence describing the picture (the target) (Bock, 1986). As such, this type of priming must not rely on any concrete lexical information, and is therefore considered to reflect priming of abstract syntactic structure.

Subsequent research has, however, revealed that lexical overlap between the prime and target sentences does increase the magnitude of the priming effect (Pickering & Branigan, 1998). The increase in the size of the priming effect when there is a content word (usually a verb) shared between prime and target sentences has been termed the "lexical boost" (Pickering & Branigan, 1998). Both of these types of syntactic priming effects have been replicated many times over (see Pickering & Ferreira, 2008 for a review of abstract and lexically-boosted syntactic priming effects), in several different languages (e.g., Hartsuiker & Kolk, 1998; Scheepers, 2003; Shin & Christianson, 2012), across languages in bilingual speakers (e.g. Hartsuiker, Pickering, & Veltkamp, 2004; Loebell & Bock, 2003; Meijer & Fox Tree, 2003; Shin & Christianson, 2009), in real world corpus data (Gries, 2005), and in children as young as 3 years old (e.g. Branigan & McLean, 2016; Huttenlocher, Vasilyeva, & Shimpi, 2004).

A meta-analysis of syntactic priming effects in production found abstract syntactic priming effects to be long-lived and cumulative, and the lexical boost to be comparatively short-lived (Mahowald, James, Futrell, & Gibson, 2016). Furthermore, recent findings comparing these two types of syntactic priming effects across children and adults in a dialog game task also revealed persistent abstract priming effects and a quickly decaying lexical boost for both groups of participants (Branigan & McLean, 2016). This reinforces past findings (Hartsuiker et al., 2008), and further suggests that different mechanisms produce abstract priming effects and the lexical boost in language production.

Mechanistic Accounts of Syntactic Priming

Understanding the causes of syntactic priming effects has become one of several fruitful lines of follow-up research on this phenomenon. Pickering and Branigan (1998) suggested that a residual activation mechanism could explain both abstract priming effects and the lexical boost. Similar to lexical priming, this account suggests that residual activation for recently processed words and their linked structural representations make a particular structure more likely to be used in subsequent utterances. When the prime and target do not share a content word, residual activation of the structural representation of the prime alone produces priming for abstract structure. When the two sentences do share a content word, residual activation for both the representation of the word and its linked structural representation yield structural priming that is then greater in magnitude than when the residual activation only occurred for the structural representation. More residual activation produces larger priming effects, under this account.

Pickering and Branigan's (1998) account is parsimonious in that it can explain both abstract priming effects and the lexical boost with the same mechanism. However, residual activation for a cognitive representation would likely be relatively short-lived. Thus, a logical prediction under this account is that syntactic priming effects should also be short-lived, meaning that the effect that a prime has on a target should dramatically decrease (or even be eliminated) when there are structurally unrelated sentences intervening between prime and target sentences. This prediction is contradicted by experimental evidence that abstract priming effects in language production persist across several (up to ten) intervening sentences without any meaningful decrease in magnitude (Bock & Griffin, 2000). The residual activation account is muddied further by additional findings that, while abstract effects appear to be long-lived, the lexical boost can decay with any intervening material (Branigan & McLean, 2016; Hartsuiker, Bernolet, Schoonbaert, Speybroeck, & Vanderelst, 2008). These findings are easier to reconcile with an account that proposes different mechanistic causes of abstract priming effects and lexically-boosted priming effects (but see Malhotra et al., 2008 for a dynamical systems explanation of an activation account that could be consistent with different longevities for abstract effects and the lexical boost).

Bock and Griffin (2000) and Chang, Dell, and Bock (2006) suggest that the abstract priming effects in production are likely due to long-term implicit learning effects, rather than short-term activation changes. Chang and colleagues instantiated this view in a computational model whereby input (from the comprehension system) helps to establish syntactic regularities, and feedback from productions (output) allow for adaptive changes in those regularities. Implicit learning occurs when repeated exposure to a particular sequence or structure changes the strengths of connections between the elements of that sequence or structure (Seger, 1994). The nature of implicit learning for syntactic structure is suggested to be error-based, in that a mismatch between predicted and processed structure yields greater learning through greater adjustments of weightings in the representational system (see Fine & Jaeger, 2013 and Jaeger & Snider, 2013). Such an account predicts cumulative abstract priming effects and larger priming effects for less frequent structures (the inverse frequency effect), both of which have been observed in recent studies of comprehension (Fine, Jaeger,

Farmer, & Qian, 2013; Fraundorf & Jaeger, 2016) and production (Kaschak, Kutta, & Jones, 2011).

Under the implicit learning account proposed by Bock and Griffin (2000) and by Chang et al., (2006), weightings between representations of individual words and the structures in which they participate are slow to change. This implies that this learning mechanism is not the cause of the lexical boost, as it manifests much earlier than this mechanism could produce. Instead, learning of verb-and-structure pairings would result in gradual weighting changes that would manifest as structural biases for individual verbs based on the overall distribution of structures in which they have been experienced. The cause of the lexical boost is suggested to be explicit memory for the wording of the prime sentence, which biases word order processing of the target (Bock & Griffin, 2000; Chang, Dell, & Bock, 2006; Chang, Janciauskus, & Fitz, 2012).

A memory-based account has also been proposed to explain abstract priming effects and the lexical boost, with different memory-based retrieval mechanisms producing each of these effects (Reitter, Keller, & Moore, 2011). Reitter, Keller, and Moore suggested that abstract priming effects are driven by a learning mechanism that affects base-level activation for syntactic chunks in long-term memory. Recently retrieved syntactic chunks have higher base-level activation, making them easier to retrieve when planning future utterances. This activation change is assumed to be somewhat slow to decay and accumulates with exposure, which can account for long-lived abstract priming effects. The lexical boost is suggested to be the product of spreading activation for recent lexical information in working memory to syntactic chunk information in long-term memory. Information in working memory is ephemeral in nature, and so this mechanism accurately predicts a short-lived lexical boost. By implementing these mechanisms in an ACT-R computational model, Reitter and colleagues were able to simulate many behavioral findings in production, such as the inverse frequency effect and cumulative priming effects.

Syntactic Priming in Comprehension

Syntactic priming has been mostly investigated in language production paradigms. However, many complementary studies on comprehension have emerged in the last decade (see Tooley & Traxler, 2010 for a review). Initially, findings from trial-to-trial priming studies noted an asymmetry between comprehension and production whereby lexically-mediated priming effects were widely observed in the absence of abstract priming effects (Arai, van Gompel, & Scheepers, 2007; Carminati, van Gompel, Scheepers, & Arai, 2008; Ledoux, Traxler, & Swaab, 2007; Tooley, Traxler, & Swaab, 2009). However, abstract priming effects have now been observed in a growing set of comprehension studies (Kim, Carbary, & Tanenhaus, 2013; Pickering, McLean, & Branigan, 2013; Thothathiri & Snedeker, 2008; Tooley & Bock, 2014; Traxler, 2008), most notably in studies that show cumulative priming for a syntactic structure over the course of the study, rather than trial-to-trial priming effects (Fine et al., 2013; Fraundorf & Jaeger, 2016). These findings suggest that comprehending a particular syntactic structure leads to greater ease in parsing during a subsequent experience with that structure. As in production, having the same verb in both of those sentences increases the size (and detectability) of this effect.

Importantly, studies that directly compare priming effects in the comprehension and production modalities have found no reliable differences in how these effects manifest across modality (Segaert, Kempen, Petersson, & Hagoort, 2013; Tooley & Bock, 2014). Such findings are consistent with the idea that priming in comprehension occurs as a response to changes in syntactic regularities outputted by the production system. It therefore seems likely that the same core mechanisms produce syntactic priming effects in comprehension and production. If this is true, then we would expect to find long-term learning of abstract structure in comprehension. As predicted, several studies have obtained (long-lived) cumulative abstract priming effects in comprehension (Fine & Jaeger, 2016; Fine, Jaeger, Farmer, & Qian, 2013; Fraundorf & Jaeger, 2016; Kaschak & Glenberg, 2004). Additionally, Wells, Christiansen, Race, Acheson, and MacDonald (2009) have found that repeated exposure to difficult object-relative clauses, over several sessions, reduces the difficulty associated with comprehending that structure. Together, these findings strongly support implicit learning of syntactic structure across comprehension episodes.

A shared mechanisms view would predict a short-lived lexical boost in comprehension (as in production). However, the two studies that have investigated the longevity of the lexical boost in comprehension have found lexically-boosted effects that persisted across two to three intervening sentences (Pickering, McLean, & Branigan, 2013; Tooley, Swaab, Boudewyn, Zirnstein, & Traxler, 2014). Only finding persistence of this effect in comprehension could reflect differences in the task demands between production and comprehension studies. Specifically, production tasks require a message-level representation before language is produced, whereas comprehension tasks often entail more passive listening or reading. Such deeper processing in production would likely lead to stronger propositional representations of the meaning of the sentence, but weaker memory for surface-level features of the sentence, like the exact wording. This would imply that effects on target processing that are driven by explicit memory for a particular word (i.e., verb) in the prime sentence would be more robust in comprehension tasks. If so, then both memory accounts of the lexical boost (Bock & Griffin, 2000; Reitter et al., 2011) would predict a more long-lived lexical boost in comprehension than in production. On the other hand, the persistence of the lexical boost in comprehension may also suggest that it is caused by a long-lived learning mechanism, like abstract priming effects. The current study addresses the latter possibility.

The Current Study

The goal of the current study is to determine whether a single long-term learning mechanism can account for lexically-mediated as well as abstract syntactic priming effects in comprehension. If abstract learning for structure is taking place in comprehension, then we predict that a difficult syntactic structure will become easier to process as exposure to the structure increases across multiple processing sessions. If lexically-mediated syntactic priming is likewise caused by this learning based mechanism, then the immediate effect of a prime on a target sentence (that share the same syntax and verb) should change as learning of the structure increases across sessions (See Figure 1, panel C). Additionally, this immediate, lexically-mediated priming effect may depend on which verbs have been encountered in that structure on previous sessions. Here, we are also testing whether

learning of the structure differs depending on the specific verb-structure pairings that have been encountered in the study sessions.

To investigate these questions, participants took part in five eye tracking sessions during which they read difficult reduced-relative (garden-path) sentences (see example sentences, below). These sentences were presented one at a time, but were arranged in pairs such that a prime sentence was immediately followed by a target sentence, and the prime and target sentences always contained the same initial verb (which is a past participle in this syntactic structure). Half of the sentence pairs in each session contained initial verbs that appeared in the reduced-relative structure on all sessions, and half contained verbs that did not appear in that structure on any other session.

Reduced-relative prime-target pair

a) Prime: The speaker selected by the group would work perfectly for the program.

b) Target: The architect selected by the manager was educated at Yale.

Fixation times at the verb and disambiguating "by-phrase" regions of the reduced-relative sentences were used as measures of processing difficulty of the structure. Fixation times on the prime sentences (baseline estimate of the structure) and target sentences (where lexically-mediated priming is evident) were modeled using multi-level modeling techniques. These measures were used to investigate possible implicit learning and lexically-mediated syntactic priming effects of the reduced-relative structure.

We intentionally use the term "lexically-mediated priming" rather than the "lexical boost." This is meant to convey that we are not focused on comparing target processing when the target has the same structure as the prime relative to when the target shares the same structure *and* verb as the prime. We therefore, cannot claim that priming with verb overlap is "boosted" relative to priming without verb overlap, or "dependent" on verb overlap. Rather, we are specifically interested in whether the facilitation that occurs when there is both structural *and* lexical overlap between primes and targets is produced by the same learning mechanism that produces (abstract) cumulative structural priming effects in comprehension. Lexically-mediated priming effects have been observed in previous comprehension studies using this structure (Ledoux et al., 2007; Tooley et al., 2009), and have been shown to persist across at least three intervening sentences (Tooley et al., 2014). Thus, these effects tend to behave more like abstract priming effect in production, and so might also be the result of an abstract learning mechanism.

If the learning mechanism that yields cumulative syntactic priming effects in comprehension is also responsible for trial-to-trial priming when primes and targets share the same verb and structure, then the size of this effect should change as learning for the structure increases. Furthermore, if lexically-mediated priming is due to a learning mechanism, then this verb-structure learning may be stronger for verbs that have been encountered in the reduced-relative structure on previous sessions. If this is the case, then we should find differential effects for sentences processed with a novel verb compared to sentences processed with a previously encountered verb, in the reduced-relative structure.

Implicit learning of the structure would be indicated by decreasing fixation times for the prime sentences as exposure to the structure increases over the five sessions, and this learning should persist across all sessions. If lexically-mediated priming due to lexical and structural overlap between the prime and target takes place, then fixation times of the target sentences should be decreased relative to the prime sentences. However, if these two sources of facilitation are due to separate underlying mechanisms, then we should find that overall ease of processing the structure decreases across the five sessions, but the difference between prime and target fixation times remains effectively unchanged from one session to the next. More generally, the long-term learning for the structure should not affect the size of lexically-mediated priming, if it is caused by a different, more short-lived mechanism.

Method

Participants

50 undergraduates from the University of California, Davis participated in this study. They received either 1 course credit or $10 per hour in exchange for their participation. Participants who completed the study were compensated for five hours of participation. All participants gave informed consent to participate, were native English speakers with normal (or corrected-to-normal) 20/20 vision, and had no history of language impairments.

Stimuli and Design

The experimental stimuli in each of the five sessions consisted of 24 prime-target pairs of reduced-relative sentences (see sentences a and b, below), and 24 prime-target pairs in which the prime sentence is a reduced-relative and the target sentence is a past tense main clause sentence (see sentences c and d, below). The initial verb in each pair is the same in the prime and target sentences. The 24 reduced-relative/main clause prime-target pairs with the same verbs were added to eliminate the possibility of strategic effects by the participants; thus, a repetition in the initial verb of a sentence was accompanied by a repetition in the structure of the sentence 50% of the time and a different structure 50% of the time.

Two versions of the experiment were created such that if a verb appeared in a reduced-relative sentence on version A, then that verb appeared in a main clause sentence on version B, and vice versa. To ensure that the meanings of the sentences across the two versions were as similar as possible, pairs of verbs that were similar in meaning were chosen (e.g., selected/picked). This meant that the 24 verbs that appeared in the reduced-relative pairs on version A were similar in meaning to the 24 verbs that appeared in the reduced-relative pairs on version B. These two versions were also used to counterbalance the position of the experimental sentences, such that each prime sentence (on version A) served as a target sentence (on version B). This counterbalancing technique allows us to compare across prime and target sentences using the exact same sentences, controlling for length and frequency effects in the experimental stimuli (see example stimuli, below).

Version A: Reduced-relative prime-target pair

c) Prime: The speaker selected by the group would work perfectly for the program.

d) Target: The architect selected by the manager was educated at Yale.

Version A: Reduced-relative/main clause pair

e) Prime: The host picked by the manager had the prettiest smile.

f) Target: The boy picked the puppy with the big spot on its back.

Version B: Reduced-relative prime-target pair

a) Prime: The architect picked by the manager was educated at Yale.

b) Target: The speaker picked by the group would work perfectly for the program.

Version B: Reduced-relative/main clause prime-target pair

c) Prime: The host selected by the manager had the prettiest smile.

d) Target: The boy selected the puppy with the big spot on its back.

Two filler sentences intervened between each of the prime-target pairs, but because half of the target sentences were main clauses, this should not have been overly apparent to participants. Half of the filler sentences were past-tense main clause sentences (such as e), and half were past-tense relative clause sentences with the word “that” and no by-phrase (such as f). The ordering of these types of fillers throughout the study was random, and each participant received the same ordering of fillers.

g) The rooster escaped the coop only to be chased by a cat.

h) The lender that approved the loan negotiated a good interest rate.

To assess whether learning of the structure differs based on the specific verbs that are encountered in that structure, 12 of the verbs that appeared in the RR-RR prime-target pairs on session one, also appeared in RR-RR prime-target pairs on sessions two through five. The other 12 verbs were unique to each of the five sessions. The 12 verbs that appeared in all five sessions will be referred to as the “trained” verbs (see Appendix A for a stimuli breakdown, including which verbs were “trained”). The number of days between any two eye tracking sessions for any one participant varied randomly between one and six days.[1]

Apparatus/Procedure

A Fourward Technologies Dual Purkinje Image Eye Tracker monitored participants’ eye movements while they read the experimental stimuli. The tracker has angular resolution of 10’ of arc. It monitors only the right eye’s gaze location. A PC displayed materials on a VDU 70 cm from participants’ eyes. The display consists of Borland C default font with approximately 4 characters per degree of visual angle. The location of participants’ gaze was sampled every millisecond and the software recorded the tracker’s output to establish the sequence of eye fixations and their start and finish times.

At the beginning of the study, the experimenter seated the participant at the tracker, and positioned the participant in chin and head rests to minimize head movements. The tracker was first aligned and calibrated, and then the experiment began. The participants read four

[1]Due to eye tracker malfunction and repair, 12 participants had a lag longer than six days between two of their eye tracking sessions.

practice sentences and responded to two practice questions to familiarize them with the procedure, and then proceeded to the experimental sentences. To signal that they had finished reading each sentence, the participant pressed a handheld button. The participants responded to comprehension questions (with one of two button presses) after 19 of the filler sentences and 6 of the RR targets; they did not receive feedback on their responses. Between each trial, a pattern of boxes appeared on the computer screen along with a cursor that indicates the participant's current gaze location. This allowed the experimenter to assess the calibration of the eye tracker as the study progressed. If calibration loss was observed by the experimenter, the eye tracker was recalibrated before proceeding with the next sentence.

Data Analysis

Three sentence regions were examined in the analysis of these data. The verb region refers to the time participants spent fixating at the initial verb of the sentence. The by-phrase region consists of the word "by" and the noun phrase that accompanies it (*by the group*, in the example sentences above). This region is the most critical region theoretically, as it is the point in the sentence where processing costs are most apparent. The post-target region contains the two words immediately following the disambiguating region.

For each of the sentence regions mentioned, two measures of fixation were analyzed: first-pass time and total time. The first-pass time measure is the sum of all fixations in a region until fixating out of that region. The total time measure includes all the time spent in a sentence region. This measure includes first-pass time as well as time spent in a region after having fixated into another region and then fixated back into the original region. All fixation times less than 120 msc or greater than 3000 msc were excluded from analyses (based on the procedures followed by other published eye tracking studies of syntactic priming with reduced-relatives; e.g. Traxler & Tooley, 2007; Tooley, Traxler, & Swaab, 2009).

Analyses were carried out in R (R Development Core Team, 2008). Linear mixed effects models with random-slopes-and-intercepts (Baayen, Davidson, & Bates, 2008; Jaeger, 2008) were used to estimate fixation times on the critical sentence regions (listed below) of the experimental stimuli. All models estimated random effects based on item and participant identity simultaneously. The maximal version of the models (warranted by the design) was used. If the maximal model would not converge, random effects were removed based on the size of their variance components (smaller effects were removed first) until the model reached convergence. The random effects structure of each model is included in the model output tables.

Separate models were fit to estimate implicit learning effects across sessions, and priming effects at the target sentences due to the previously processed prime sentence. The models of implicit learning effects estimated fixation times on the prime sentences only. Prime sentences are always preceded by filler sentences, and so they serve as our baseline estimate of processing difficulty for the reduced-relatives overall. Centered fixed effects of Session, Training, and Item Order (and all possible interactions) were included in these models. "Session" corresponds to the session number in which the fixation times were recorded (1, 2, 3, 4, or 5), and reflects the graded increase in cumulative number of exposures to the reduced-relative structure. "Training" differentiates whether or not the verb in a given

sentence was encountered (in the reduced-relative structure) on a previous session (12 verbs were the same across all five sessions). Item Order refers to the numerical ordering of the sentences in a given session, taking into account primes, targets, and fillers. This variable was included to account for any reduction in fixation times due to the participants adapting to the eye tracking procedure (Fine, Jaeger, Farmer, & Qian, 2013). With this predictor included in the models, we can be sure that a significant effect of Session reflects learning of the structure, and not adaptation to our task.

If learning of the reduced-relative structure is taking place over the five sessions, we should find a significant effect of Session, whereby the prime sentence fixation times decrease as session number increases. If processing the structure is different for instances where a verb has been previously encountered in the structure, then we should find a significant effect of Training. This would most likely manifest as fixation times for sentences with trained verbs being decreased compared to sentences with novel verbs (for that structure). If this verb-and-structure learning takes multiple sessions to manifest, we may also find an interaction between Session and Training, where sentences with "trained" verbs are processed faster, but only in later sessions.

The overall models of immediate priming effects estimated fixation times of both primes and target sentences. Centered fixed effects of Position, Session, Training, and Item Order (and all possible interactions) were included in these models. "Position" refers to whether or not the sentence was encountered in the prime or target position (each sentence appeared in both positions an equal number of times due to counterbalancing). Models estimating fixation times on primes and targets for each individual session were run for regions and time measures that yielded a significant interaction with the Session variable, in the overall model. These models included centered predictors of Item Order and the variable that interacted with the Session variable.

If target sentences are being primed due to the processing of the previous sentence (the prime), then we should find a significant effect of the Position predictor, and faster times for target sentences compared to prime sentences. If the size of this effect changes based on the amount of exposure to the structure then we should find a significant interaction of Position with Session. If the processing advantage of the target differs based on whether the verb has been encountered in that structure before, then we should find a significant interaction of Position with Training. If priming at the target is larger for trained verbs, but only after multiple exposures of a given verb and structure combination, then we should find a significant three-way interaction between Position Session and Training, with the advantage for a trained verb being greater in later sessions.

Results

Implicit Learning Effects

Mean sentence fixation times at the critical sentence regions, across the five sessions are presented in Appendix B. In general, total prime sentence fixation times for the three critical regions decreased as session number (exposure) increased (See Figure 2). Overall models estimating fixation times on the prime sentences (see Table 1) revealed only one significant

effect for the first-pass time measure: The effect of Item Order at the By-phrase region ($p < 0.05$). Participants' initial reading times tended to decrease at the By-phrase region as more sentences were encountered, within a given session.

For the total time measure, there were significant effects of Item Order and Session at both the Verb and By-phrase regions (all p-values < 0.05). At the post-target region, there was also a significant effect of Session ($p < 0.05$). Participants tended to spend less total time fixating the Verb and By-phrase regions as the number of sentences they read (within a session) increased. Additionally, participants' total fixation times at all three critical sentence regions reliably decreased as session number increased. Notably, there were no significant effects of, or interactions with, the Training variable (all p-values > 0.05). Participants' fixation times on the prime sentences decreased across sessions regardless of whether the verb in the sentence had been encountered in the reduced-relative structure on previous sessions.

It is possible that overall decrease in total fixation times is a product of averaging across participants, and does not reflect the session over session trend in fixation times for individual participants. Inspection of the estimated slope coefficients on the Session variable for individual participants rules out this possibility. All but four of the participants had estimated negative slope coefficients for the Session variable (see Figure 3).

The model results thus far suggest a decrease in total prime fixation times across sessions. However, these models can't tell us whether the size of the average fixation times differed across adjacent sessions. To investigate this, we calculated average total fixation times for the by-phrase region of the prime sentences, in each session, for each participant in the study. We used these scores to conduct a Repeated Measures ANOVA with Session as the Independent Variable (indicating amount of exposure to the RRC structure). This ANOVA treats Session as a categorical variable and so doesn't assume a linear effect (as the MLM does). There was a significant effect of Session [$F(4, 196) = 13.77$, $p < 0.001$], which prompted us to conduct paired-samples t-tests between adjacent sessions within the study.

Though the means for each session did decrease as session number increased ($M1 = 768$ ms, $M2 = 724$ ms, $M3 = 694$ ms, $M4 = 666$ ms, $M5 = 659$ ms), the difference across adjacent sessions varied. The mean difference between Session 1 and Session 2 fixation times (44.18 ms) was significant [$t(49) = 2.14$, $p = 0.037$], the mean difference between Session 2 and Session 3 fixation times (29.63 ms) was marginally significant [$t(49) = 1.98$, $p = 0.054$], the mean difference between Session 3 and Session 4 fixation times (27.86 ms) was marginally significant [$t(49) = 1.88$, $p = 0.066$], and the mean difference between Session 4 and Session 5 fixation times (7.22 ms) was not significant [$t(49) = .482$, $p = 0.63$]. Learning, as indicated by decreases in average fixation times, was no longer reliably evident from Session 4 to Session 5.

Priming Effects at Target Sentences

The mean prime and target fixation times across the two fixation measures for each of the three critical sentence regions are presented in Table 1, above. In general, primes had longer total fixation times than targets at the verb and by-phrase regions.

Model estimates of first-pass fixation times (see Table 2) yielded significant effects of Sentence Position at the Verb region ($p < 0.05$). Participants' fixation times on the verb were faster for targets as compared to primes, which is not at all surprising considering the targets had the same verbs as the primes. At the By-phrase region, there was a significant effect of Item Order ($p < 0.05$) such that participants spent less time initially fixating the by-phrase as the number of sentences they encountered in a given session increased. At the Post-target region, there were significant effects of Session and a significant interaction between Session and Sentence Position (all p-values < 0.05). Overall, fixation times on this region were shorter for target sentences than prime sentences, however the difference between prime and target fixation times varied across sessions. In order to unpack this interaction, models estimating first-pass fixation times at the post-target region were run for each session separately. The effect of Sentence Position was not significant in individual models of any of the five sessions. However, these models did reveal large differences in the estimates of the effect of Sentence Position across sessions. Specifically, the model for session 1 estimated that *prime* fixation times were about 42 ms shorter than target fixation times, and the model for session 5 estimated that target fixation times were about 15 ms shorter than prime fixation times. This reversal in direction of the effects from one session to the other is likely driving this interaction, and is not unexpected given the variability of processing evident in the post-target region.

Models estimating total fixation times revealed significant effects of Sentence Position, Session, and Item Order at both the Verb and By-phrase regions, and significant effects of Sentence Position and Session at the Post-target region (all p-values < 0.05). Participants spent less total time fixating a target sentence (compared to a prime) across all regions analyzed. Participants' total fixation times on the verb and by-phrase also decreased as they encountered more trials within a session. Additionally, participants read the sentences faster (at all analyzed regions) as exposure to the structure increased across testing sessions. Importantly, there was no significant interaction between Sentence Position and Session, which suggests that the processing advantage of reading a sentence in the target position did not reliably change across sessions (see Figure 4). Similar to the learning models, the Training variable was again never reliably predictive of fixation time (all p-values > 0.05). Whether or not a sentence had a verb that had been encountered in the reduced-relative structure on previous sessions did not reliably influence fixation times.

Trained Verbs

The results thus far have yielded no significant effects of the Training variable or significant interactions with this variable. The strongest test of this manipulation would occur in session 5, where participants experience the reduced-relative structure in 12 sentence pairs containing verbs that have been present in this structure in all sessions. We compare processing on these sentences to sentences that contain (12) verbs that have never appeared in the reduced-relative structure on any previous session. A random-slopes and intercepts multi-level model predicting total fixation time on the critical by-phrase region using only the data from session 5 was run. This model included fixed effects of Sentence Position and Training and the Position X Training interaction, as well as crossed-random effects of participants and items. This model revealed no significant effect of the Training variable or

the Training x Position interaction ($p > 0.05$), but a significant effect of Position ($p < 0.05$): target fixation times were faster than prime fixation times for both types of sentence pairs (see Figure 5).

Comprehension Question Performance

Comprehension questions appeared after six of the reduced-relative target sentences in each of the five sessions. Performance on these particular comprehension questions can be used to gauge participants' level of attention and engagement in the reading task. If observed decreases in reading times across sessions are due to participants making less of an effort to completely process and understand the propositional meanings of the sentences, then we should see that comprehension question accuracies also decrease across sessions. Mean accuracies tended to increase from the first session to the second and third sessions (83%, 89%, 89%, respectively) and then decrease slightly for session four (86%) and session five (85%). A one-way repeated-measures ANOVA revealed no significant difference in comprehension accuracies across sessions [$F(1,49) = 0.19$, $p = 0.89$]. Comprehension performance indicative of understanding the reduced-relative structure did not reliably decrease as session number increased.

Discussion

The goal of this study was to determine whether cumulative structural priming effects and trial-to-trial lexically-mediated priming effects are produced by the same learning mechanism in comprehension. Participants read difficult reduced-relative sentences presented in prime-target pairs with the same initial verb, over five eye-tracking sessions. Baseline estimates of total fixation times for the critical regions of the reduced-relative prime sentences decreased linearly as session number increased, indicating learning of structure. A further decrease in total fixation times for the target sentences was observed, indicating a lexically-mediated priming effect. There was no significant change in the magnitude of this effect across sessions, implying that the two sources of facilitation observed in this study are separate and operate orthogonally. There was also no evidence to suggest that either of these effects were influenced by whether a specific verb had been processed in the reduced-relative structure on previous sessions. Consistent with findings in production (Branigan & McLean, 2016; Hartsuiker et al., 2008), results from this comprehension study suggest that abstract priming is being driven by implicit learning, whereas lexically-mediated priming is caused by a separate, more short-lived mechanism.

Learning of Syntactic Structure in Comprehension

Model results for prime sentences revealed a significant effect of Session at the verb, critical by-phrase, and post-target regions of the reduced-relative clauses for the total time measure. On average, fixation times decreased by about 16 ms at the verb region, 28 ms at the by-phrase region, and 22 ms at the post-target region, per session. Processing of the reduced-relative structure was therefore being facilitated as exposure increased across sessions. These results support the conclusion that learning of the reduced-relative structure took place in this study.

What is not entirely clear is whether this was learning for initial parsing decisions, reanalysis processes related to recovering from garden-path effects, or a combination of the two. Facilitation was observed primarily in the total time measure, which may suggest participants were learning to recover from an incorrect parse rather than learning to make the correct initial parse. However, it is also possible that participants strategically became more careful in an environment where they had experienced parsing difficulty, resulting in increases in first pass times that nullified learning-related speed-ups while simultaneously producing a decrease in time needed to reread the reduced-relative sentences. Both of these patterns of behavior would be consistent with our results and both could have occurred across participants in our sample. Unpacking this effect further could be a fruitful area of future research.

Though this is the first study to show long-term learning of the reduced-relative structure, across-session learning for structure in comprehension has been shown previously (Long & Prat, 2008; Wells et al., 2009). Importantly, the learning of this structure was quite long-lived, as indicated by decreases in fixation times over session lags that were at least one day apart. In theory, these implicit learning effects may still be evident for weeks or months after exposure. The durability and longevity of these effects is a topic that could be addressed in future research.

Notably, the learning effect across sessions was present alongside the significant effect of Item Order (at the verb and by-phrase regions). This means that though participants' fixation times tended to decrease as the number of sentences they read during any given session increased, comparing one session to the next still accounted for a meaningful amount of the variability in fixation times. Furthermore, the effect of Item Order was significant in both the first pass (earliest processing) and total time measures at the by-phrase region, whereas the effect of Session was only significant in this region for the total time measure. This finding is consistent with the assumption that the Item Order variable reflects general speed-ups in processing due to experience with the paradigm, and the Session variable reflects improved comprehension of the structure through increased exposure. Importantly, this means that the significant decrease in fixation times across sessions cannot be explained by participants merely becoming more comfortable reading in the eye-tracker as a session progressed.

It is also possible that the significant effect of Item Order is at least in part due to cumulative structural priming within each session, which would be consistent with previous findings (Fine et al., 2013; Fraundorf & Jaeger, 2016; Kaschak & Glenberg, 2004). However, the current study cannot speak directly to this possibility. Attempts at simultaneous modeling of learning effects across session, cumulative priming effects, and adaptation to the paradigm effects, turned out to be untenable due to issues with multicollinearity (even after transforming and centering all predictors). We do have strong evidence that learning took place in this study; it was cumulative across sessions and separate from reading speed-ups associated with adapting to the paradigm.

Lexically-Mediated Syntactic Priming Effects

The Sentence Position variable was found to be significant at all three regions in the total time measure. Model estimates suggest that fixation times for targets were faster by 30 ms at

the verb region, 46 ms at the by-phrase region, and 11 ms at the post-target region. The target sentences, which shared the same syntactic structure and initial verb as the prime sentences, were consistently processed faster than the primes. This implies that lexically-mediated syntactic priming effects occurred in addition to the long-term structural learning effects mentioned previously. Critically, the Sentence Position variable never interacted with the Session variable, suggesting that this priming effect was present in all five sessions. Additionally, it implies that the lexically-mediated syntactic priming effect did not meaningfully vary in magnitude across sessions. This result is important because it implies that learning of the primes did not impact the immediate effect of a prime on the target. Despite the decrease in processing times of the prime sentences, there was a consistent additional decrease for targets in all sessions.

This study joins others demonstrating that repeating the verb and syntactic structure across prime and target reduced-relative clause sentences leads to significant facilitation of target processing (Ledoux, Traxler, & Swaab, 2007; Tooley, Traxler, & Swaab, 2009; Traxler & Tooley, 2008). However, this is the first study showing that this lexically-mediated priming effect operates separately from more long-lived priming effects in comprehension. In addition to a long-lived learning mechanism, there also appears to be a short-term priming mechanism that facilitates syntactic structure building processes. This effect could be due to residual activation for the link between the initial verb and the reduced-relative structure node (Pickering & Branigan, 1998), explicit memory for the wording of the prime (Bock & Griffin, 2000; Chang, Dell, & Bock, 2006), or spreading activation from working memory to long-term memory (Reitter, et al., 2011). We comment further on these mechanistic accounts later in this section.

Syntactic Priming and Long-term Lexical Dependencies

No significant main effects of the Training variable were found at any sentence region for either time measure. There was no evidence to suggest that the reduced-relative sentences that contained a verb that was present in that structure on previous sessions were processed differently from those that contained novel verbs on every session. This finding was consistent across all five sessions. Tentatively, the observed implicit learning effects of the reduced-relative structure therefore appear to be lexically independent (i.e., abstract). Learning of the structure took place without reference to the particular verbs that appeared in that structure, across the five sessions. This finding is consistent with a recent comprehension study that investigated the magnitude of cumulative structural priming effects (within a single session) and found that the magnitude of the priming effect was the same whether particular verb-structure pairings were repeated in the session, or not (Fine & Jaeger, 2016).

Additionally, no significant Position by Training Interaction was found at any of the sentence regions analyzed, for either time measure. Importantly, this was observed in an analysis of Session 5 alone, where the “trained” verbs had been experienced in the reduced-relative structure the most times. This means that the magnitude of the lexically-mediated priming effect was not influenced by whether a specific verb had appeared in the reduced-relative structure on previous sessions. Though the priming effects observed in this study

were lexically-mediated within a short time frame, this effect did not generalize to instances where the lexical overlap was separated by a longer time lag. Critically, this reaffirms our conclusion that lexically-mediated priming is not a form of learning, and thus it is unlikely that this priming effect and structural biases inherent to particular verbs share a common mechanism. This conclusion is consistent with those drawn from recent findings in production (Branigan & McLean, 2016).

Naturally this null result must be interpreted with caution. It is entirely possible that the manipulation used in the current study to "train" specific verbs within a given structure was not sufficient to evoke these effects, or that these effects were not detectable by our data analyses. Perhaps more sessions with the same verbs, or more exposures to the same verbs within each session would have produced observable training effects. Though one production study involving mass amounts of exposure for a particular verb-structure pairing within one session obtained a lexical-structural preference (Coyle & Kaschak, 2008), it remains to be seen whether this effect would persist across sessions on separate days, or be observable in a measure of comprehension.

It is also possible that training effects would have been found had there not been such a long time lag between sessions. During the day(s) between sessions, participants likely encountered the same verbs used in the experimental stimuli in their daily lives, and the rarity of the reduced-relative structure makes it unlikely that these verbs appeared in that structure. Processing the experimental verbs in different structures during the session lags could have nullified any training benefits gained from processing those verbs in the reduced-relative structure. Future comprehension studies, perhaps with massed exposure to a particular verb-structure pairing across multiple sessions, would be useful in further addressing this question.

Dual Mechanism Account of Syntactic Priming Effects in Comprehension

Both implicit learning and lexically-mediated priming of the reduced-relative structure were observed in the current study. Importantly, the lexically-mediated priming effects did not reliably interact with the implicit learning effects. This result implies that lexically-mediated priming in comprehension is not produced by a learning mechanism. Furthermore, these results provide evidence for two separate, and apparently orthogonal, mechanisms producing syntactic facilitation in comprehension. This conclusion is consistent with dual mechanism accounts that have been proposed to explain syntactic priming in language production (Branigan & McLean, 2016; Hartsuiker et al., 2008).

One side of this dual mechanism account must include long-term learning of syntactic structure to adequately explain the current (and past) results. Bock and Griffin (2000) characterize this learning as the strengthening of the network connections between the representational units that support the use of syntax. Repeated building of a particular structure strengthens the procedural processes involved in formulating that structure. This mechanism is suggested to drive abstract syntactic priming effects in both language comprehension and production (Bock & Griffin, 2000; Chang, Dell, & Bock, 2006) and is instantiated in an error-driven fashion where greater learning occurs for less predictable structures (Jaeger & Snider, 2013). Furthermore, this view suggests a tight coupling between

adaptation in comprehension and production. Comprehension priming can be viewed as an adaptive response to the output of the production (and prediction) system. Re-using the same structure in speech happens because it becomes easier with use, and this adaptation changes what a listener may expect to hear in a given language context. An alternative account (Reitter et al., 2011) suggests that this learning is a manifestation of increased base-level activation for recently encountered structural information in long-term memory. According to this model, base-level activation for a given structure increases (and accumulates) with repeated exposure, producing structural facilitation that is cumulative and long-lived.

Findings from the current study may help adjudicate between these competing accounts of the mechanisms underlying cumulative structural priming effects (though, we note that the Reitter et al. (2011) model was formulated specifically for production processes). The learning effect observed in this study decreased in magnitude in the later sessions (though the amount of exposure to the structure remained constant). The error-driven learning account predicts that the benefit of increased exposure to a structure will decrease as that structure is learned (because the error signal becomes weaker with greater structural exposure). The Reitter et al., model predicts no such asymptote in the learning effect (given a consistent amount of exposure), and instead predicts that structural facilitation will increase with exposure until some natural processing floor is achieved. The tapering off of the learning effect (observed in the primes) is unlikely to be a processing floor as target fixation times were decreased relative to primes, even in Session 5. The error-based implicit learning mechanism (Chang et al., 2006; Jaeger & Snider, 2013) is therefore most compatible with the learning effects observed in this study.

This error-driven learning account would therefore also predict that the magnitude of trial-to-trial, abstract priming effects should decrease as exposure to the structure increases. Though our trial-to-trial effects involved repetition of a verb-and-structure coupling, it is still the case that the same structure was repeated across prime and target trials. In theory, this means that some part of the trial-to-trial effect should be due to abstract priming, and so may change with increased exposure to the structure. However, we found no evidence of a modulation in the size of our trial-to-trial priming effect across sessions. Perhaps any effect due solely to structural overlap from prime to target did decrease across sessions and it was simply too small to detect it in our measurement of a lexically-mediated, trial-to-trial priming effect. Either way, this finding is consistent with our conclusion that the major driver of the observed lexically-mediated priming effect is not a learning mechanism.

We now consider how our results can be used to help identify the mechanism responsible for lexically-mediated priming. First, our results suggest this mechanism is separate from, and more short-lived than the abstract learning mechanism. It is possible that residual activation for the prime's verb and linked structural representation facilitated activation for those representations during target processing (Pickering & Branigan, 1998). However, recent findings that lexically-mediated priming in comprehension persists across two or three intervening sentences (Pickering, Branigan, & McLean, 2013; Tooley et al., 2014) are harder to reconcile with a residual activation account in which activation decays relatively quickly. Alternatively, explicit memory for the wording of the prime may have influenced predictions about the wording of the targets (Bock & Griffin, 2000; Chang, Dell, & Bock, 2006). It is

also possible that both explicit and implicit memory (not learning) combined to produce the observed lexically-mediated priming effects. Both of these possibilities yield predictions that are consistent with the current results: Lexically-mediated priming is shorter-lived than structure-learning effects. As such, the results of the current study cannot support one account over another.

The Reitter et al. (2011) model offers a more specific prediction to test. This model suggests that a linking of lexical information in working memory to structural information in long-term memory produces lexically-mediated priming. The weightings of the lexical information decrease as the number of words held in working memory increases. This implies that lexically-mediated priming effects should be weaker when there are more words in the prime sentence (held in the working memory buffer), because the repeated verb would have weaker links to the structural information in long-term memory. We ran follow-up analyses that included prime sentence length as a fixed effect when estimating the difference between the total fixation times for primes and targets at the critical by-phrase. These analyses yielded no significant modulation of the priming effect based on the length of the prime sentence. This null result does not support the Reitter et al. (2011) model's prediction, but it does not contradict it either. Additional research is needed to investigate this prediction more thoroughly, as well as to compare these competing accounts more precisely in order to identify the mechanism that produces lexically-mediated priming.

Limitations

One limitation of this study is that we were unable to establish the number of exposures necessary to produce abstract learning effects for the reduced-relative structure. We showed that the number of exposures within one session (36) was sufficient to change how participants processed the reduced-relative structure, but were unable to model trial-level cumulative priming effects (that were separable from adaptation to the paradigm effects). Though not changing our overall conclusions, successfully modeling this effect would have enabled us to compare trial-level cumulative priming effects for the reduced-relative structure to those for other structures (e.g., Fine et al., 2013).

We are also limited in the conclusions that we can draw because this is the first on-line comprehension study that has investigated long-term structure learning alongside short-term, lexically-mediated priming effects. Additional, similar studies are needed to replicate and extend these findings. Furthermore, we examined one particular structure, and one that lacks the optionality inherent to many of the structures tested in production (i.e., active/passive or dative double-object/prepositional object). A direct comparison of our results to those in Production is therefore not straightforward, and would also require additional research.

Conclusions

The current study investigated whether cumulative structural priming and lexically-mediated priming share a common learning-based mechanism in language comprehension. Evidence of cumulative structural priming, that operated alongside orthogonal lexically-mediated priming, suggests a learning mechanism produces the former but not the latter set. The cumulative learning effect tapered off in later sessions, consistent with an error-based

learning mechanism (e.g., Jaeger & Snider, 2013). Neither effect was modulated by whether the verb had been encountered in the learned structure on previous sessions. These results support a dual mechanism account of syntactic priming effects in comprehension, whereby cumulative priming is produced by a learning mechanism and lexically-mediated priming is produced by a more short-lived mechanism.

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Appendix A: Experimental Stimuli

Sentences are presented in prime-target pairs. Individual sentences in each pair appeared in the prime position, and in the target position on different versions of the experiment (between-subjects). The two verbs in each sentence represent the verbs that appeared in that sentence across the two versions of the experiment (Version A/Version B).

Session1

The speaker selected/picked by the group would work perfectly for the program.

The architect selected/picked by the manager was educated at Yale.

The director watched/observed by the cop was in a bad part of the town.

The mouse watched/observed by the cat was hiding under the table.

The assistant graded/evaluated by the professor was very interesting.

The leader graded/evaluated by the participant was well-liked.

The mailman expected/anticipated by the secretary arrived too late.

The deliveryman expected/anticipated by the woman was right on time.

The prisoner transported/moved by the guards was closely watched.

The hostage transported/moved by the captors was very worried.

The teacher loved/adored by the class was very easy to understand.

The singer loved/adored by the fan was unable to make it to the concert.

The thief identified/recognized by the victim was held for questioning.

The victim identified/recognized by the doctor was in bad shape.

The troops attacked/assaulted by the terrorists suffered heavy losses.

The army attacked/assaulted by the rebels moved forward quickly.

The client wanted/desired by the advertiser was worth a lot of money.

The actress wanted/desired by the director was hesitant to confirm.

The teacher appreciated/valued by the principal worked very hard.

The secretary appreciated/valued by the accountant was very knowledgeable.

The protester angered/enraged by the politician shouted obscenities at the reporter.

The conservative angered/enraged by the liberals plotted revenge.

The rebels battled/fought by the security forces fled into the jungle.

The insurgent battled/fought by the regiment was unable to triumph.

The cowboys surrounded/encircled by the indians were very worried.

The lions surrounded/encircled by the hunters paced nervously.

The driver stopped/halted by the policeman had been drinking.

The child stopped/halted by the lifeguard looked very upset.

The voter convinced/persuaded by the mayor was mighty pleased.

The consumer convinced/persuaded by the salesman was pleasantly surprised.

The actor copied/imitated by the understudy performed brilliantly.

The genius copied/imitated by the children was running late.

The dog found/discovered by the hunter had a broken leg.

The bird found/discovered by the scientist acted calm and unbothered.

The child scolded/punished by the babysitter went up the stairs.

The man scolded/punished by the policeman was very embarrassed.

The motorist injured/wounded by the truck driver had to go to the hospital.

The child injured/wounded by the dog breathed heavily.

The homeowner frightened/scared by the burglar ran outside.

The horse frightened/scared by the boy ran hurriedly away.

The spy caught/captured by the FBI agent disappeared forever.

The criminal caught/captured by the detective was in a state of panic.

The countess offended/disgusted by the peasant swore revenge.

The tutor offended/disgusted by the delinquent stormed out of the room.

The trapper hunted/stalked by the cougar escaped in the end.

The owl hunted/stalked by the eagle circled frantically.

The passengers delayed/postponed by the pilot were furious.

The woman delayed/postponed by the taxi driver started to shout.

Session 2

The student selected/picked by the committee got a large scholarship.

The singer selected/picked by the bride sang all through the reception.

The player watched/observed by the scout was having a very bad game.

The lady watched/observed by the secret agent was eating alone.

The girl expected/anticipated by the boy never showed up for their date.

The teacher expected/anticipated by the students arrived very late.

The burro transported/moved by the trailer was going to New Mexico.

The dancer transported/moved by the taxi was heading to rehearsal.

The Labrador loved/adored by the family enjoyed playing fetch.

The cook loved/adored by the woman made delicious lasagna.

The pick-pocket identified/recognized by the man had stolen twelve wallets.

The murderer identified/recognized by the witness maintained his innocence.

The speaker attacked/assaulted by the mob had unpopular political views.

The camper attacked/assaulted by the bear managed to scare it off.

The pitcher wanted/desired by the team had an amazing fast ball.

The decorator wanted/desired by the couple had a waiting list two months long.

The apprentice appreciated/valued by the carpenter was learning very quickly.

The model appreciated/valued by the man had the most beautiful smile.

The clerk angered/enraged by the customer called for the manager.

The coach angered/enraged by the player threw his clipboard to the ground.

The team battled/fought by the opponents refused to give up on the game.

The samurai battled/fought by the ninja was not fast enough to win.

The students helped/assisted by the counselors were very grateful.

The surgeons helped/assisted by the nurses were exhausted.

The miners rescued/saved by the paramedics recovered slowly.

The man rescued/saved by the sailor was soaking wet.

The senator advised/counseled by the general spoke to the press.

The girl advised/counseled by the parent stayed at home that night.

The carpenter questioned/quizzed by the inspector wanted to go home.

The butler questioned/quizzed by the widow remained calm.

The girl fascinated/captivated by the monkey gave him her ice cream cone.

The child fascinated/captivated by his friend got very excited.

The deer killed/slaughtered by the speeding truck caused a large accident.

The turkey killed/slaughtered by the farmer would be eaten on Thanksgiving.

The teenager ignored/overlooked by the store clerk was very frustrated.

The hobo ignored/overlooked by the train conductor snuck aboard.

The woman hated/loathed by the deliveryman was always rude.

The doctor hated/loathed by his patients had a terrible bedside manner.

The racehorse inspected/checked by the doctor was able to race the next day.

The cat inspected/checked by the judge won a prestigious award.

The lion mauled/mangled by the bear was removed from the circus.

The photographer mauled/mangled by the tiger was sore for weeks.

The juror accused/blamed by the judge was not allowed back in the courtroom.

The employee accused/blamed by the supervisor was asked not to return to work.

The army ambushed/trapped by the revolutionaries suffered heavy losses.

The pirates ambushed/trapped by the prisoners lost all of their gold.

Session 3

The manager selected/picked by the owner had a long history of success.

The swimmer selected/picked by the coaches would represent the team at the finals.

The crowd watched/observed by the security agents was getting a little rowdy.

The fisherman watched/observed by the child caught many fish.

The contestant graded/evaluated by the judges had been practicing all week.

The diver graded/evaluated by the trainer was not able to jump high enough.

The roommate expected/anticipated by the rest of the house was in good spirits.

The driver expected/anticipated by the attorney had gotten into an accident.

The people transported/moved by the ferry had to leave their cars behind.

The jockey transported/moved by the racehorse was in another universe.

The convict loved/adored by the attorney died in prison.

The prince loved/adored by the witch was tricked into marrying her.

The witnesses identified/recognized by the criminals had to flee for their lives.

The waiter identified/recognized by the chef was wanted in three states.

The girl attacked/assaulted by the chimpanzee lost two fingers.

The man attacked/assaulted by the clown had been teasing him for hours.

The leader wanted/desired by the church was not liked in the congregation.

The politician wanted/desired by the people was a charming individual.

The volunteers appreciated/valued by the event planner were given free dinner.

The adviser appreciated/valued by the student helped him select a class schedule.

The bird angered/enraged by the squirrels pelted them with seeds.

The friend angered/enraged by the situation was not behaving like herself.

The chief battled/fought by the new-comer was not overthrown.

The crowd battled/fought by the police was terribly angry and violent.

The child thrilled/excited by the movie let out a loud cry and smiled broadly.

The girl thrilled/excited by the actor on television completely forgot what she was doing.

The king pleased/delighted by the gift was in good spirits.

The baby pleased/delighted by the toy finally stopped crying.

The turtle covered/buried by the landslide dug furiously.

The crab covered/buried by the sand felt safe from the circling birds.

The woman astounded/amazed by the product bought five boxes.

The child astounded/amazed by the spaceship launch started reading books on space.

The man lifted/hoisted by the elephant was not very confident.

The monkey lifted/hoisted by the trainer was hoping for a treat.

The goalie shoved/pushed by the referee became very upset.

The woman shoved/pushed by the robber began to scream for help.

The lady grabbed/seized by the man narrowly missed being struck by a car.

The mouse grabbed/seized by the eagle was frozen with fright.

The lawyer pulled/yanked by the boy made a stern face.

The girl pulled/yanked by her father wanted to stay at the zoo longer.

The Girl Scout startled/alarmed by the old woman dropped her box of cookies.

The dog startled/alarmed by the intruder let out a deafening howl.

The man shunned/rejected by the woman left the bar and went straight home.

The student shunned/rejected by the classmate learned to hate school.

The pitcher replaced/substituted by the coach threw his glove into the dugout.

The actor replaced/substituted by the director thought his career was over.

The policeman interrogated/grilled by the commissioner swore he was innocent.

The victim interrogated/grilled by the attorney stayed very calm and collected.

Session 4

The child selected/picked by the captain could run very fast.

The winner selected/picked by the group had come up with the best proposal.

The racers watched/observed by the volunteers stayed inside the race track.

The ponies watched/observed by the children had long beautiful manes.

The workers graded/evaluated by the mayor were wasting time on the job.

The missionaries graded/evaluated by the priest had converted many people.

The army expected/anticipated by the general had traveled a long way.

The bees expected/anticipated by the farmer would pollinate the crops.

The babies transported/moved by the mother would now be safe from harm.

The clams transported/moved by the fisherman would fetch a pretty price.

The athletes loved/adored by the fans were in amazing shape.

The guitarist loved/adored by the townspeople played long into the night.

The kitten identified/recognized by the boy had been missing for a week.

The bird identified/recognized by the scientist was believed to be extinct.

The thug attacked/assaulted by the gang was in the wrong part of town.

The protestors attacked/assaulted by the cops had chained themselves to trees.

The parrot wanted/desired by the pirate was hidden under a palm tree.

The catcher wanted/desired by the agent would make him very rich.

The cows appreciated/valued by the rancher had kept his business afloat.

The teenagers appreciated/valued by the store purchased lots of magazines.

The gangsters angered/enraged by the beating were plotting revenge.

The dragon angered/enraged by the knight blew fire from his snout.

The dueler battled/fought by the masked man was performing quite well.

The monkey battled/fought by the cat had stolen his dinner.

The player praised/complimented by the talent scout was soon offered a scholarship.

The pupil praised/complimented by the tutor studied extra long that week.

The child teased/tormented by the bully was not at school the next day.

The girl teased/tormented by the boy promised to never talk to him again.

The woman abducted/kidnapped by the stalker managed to escape.

The man abducted/kidnapped by the spy refused to tell what he knew.

The shortstop cheered/encouraged by the pitcher threw the runner out at home.

The child cheered/encouraged by the teacher spelled the word correctly.

The manager looted/ransacked by the protestors called the police immediately.

The attorney looted/ransacked by the criminal lost many important documents.

The mother kissed/smooched by the toddler gave him a hug in return.

The girl kissed/smooched by the celebrity got so excited that she fainted.

The professor honored/revered by the Dean received a corner office.

The secretary honored/revered by the company got an extra day off.

The swimmer tired/fatigued by the coach had to quit early.

The woman tired/fatigued by the children put them down for naps.

The doctor cured/healed by the specialist went back to work.

The nurse cured/healed by the medicine had been very ill.

The principal fired/sacked by the school board had been missing work.

The accountant fired/sacked by the firm was arrested for drug possession.

The firemen drenched/soaked by the helicopter drop began to hike uphill.

The girl drenched/soaked by the clown never went to another circus.

The man fooled/tricked by the magician did not receive a prize.

The policeman fooled/tricked by the disguise let the man go free.

Session 5

The horse selected/picked by the trainer had a promising future.

The man selected/picked by the society was asked to join in secret.

The widow watched/observed by the nephew had been acting very strange.

The mouse watched/observed by the student navigated the maze with ease.

The performers graded/evaluated by the audience were not very talented.

The seamstress graded/evaluated by the shop owner sewed very quickly.

The trolley expected/anticipated by the pedestrian was a big relief.

The physicist expected/anticipated by the dean had exciting news to share.

The herd transported/moved by the caravan was heading toward Arabia.

The choir transported/moved by the bus was practicing scales.

The woman loved/adored by the older man refused to marry him.

The boss loved/adored by the employees was given a bouquet of roses.

The lady identified/recognized by the detective was not who she claimed to be.

The hunter identified/recognized by the guide had been poaching for years.

The snake attacked/fought by the mongoose hissed loudly in fury.

The captain attacked/fought by the deck hand had refused to share his whiskey.

The designer wanted/desired by the actor made the wonderful clothes.

The baker wanted/desired by the bakery had a glowing reputation.

The plumber appreciated/valued by the town was always available.

The gardener appreciated/valued by the duke loved his work.

The student angered/enraged by the professor stopped attending classes.

The girl angered/enraged by the guardian was not allowed to go to the party.

The men battled/fought by the savages succumbed to the poisoned darts.

The fleet battled/fought by the submarine had to flee back to a safe harbor

The supplier cheated/conned by the manufacturer refused to carry their product.

The landlord cheated/conned by the couple was not paid any rent.

The waitress preferred/favored by the customer got a large tip.

The attorney preferred/favored by the judge was always on time.

The athlete coached/trained by the dancer became much more flexible.

The man coached/trained by the gym owner lost fifteen pounds.

The girl taught/instructed by the chef made a wonderful soufflé.

The student taught/instructed by her mother got straight A’s.

The singer missed/skipped by the conductor was left at the theater.

The child missed/skipped by the teacher did not receive a cookie.

The baker hired/employed by the market made eight different kinds of bread.

The manager hired/employed by the owner had to work seven nights per week.

The girl washed/cleaned by her mother was covered in spaghetti.

The doctor washed/cleaned by the nurse was prepping for surgery.

The man burned/scorched by the flames covered his face and ran.

The woman burned/scorched by the tanning bed looked like a lobster.

The stylist pampered/spoiled by the magazine decided to take a job there.

The child pampered/spoiled by the relative ate ice cream every day.

The chef punished/disciplined by the manager had to work three extra shifts.

The apprentice punished/disciplined by the craftsman had to clean up the workshop.

The captain worried/concerned by the storm stayed awake all night long.

The parents worried/concerned by the teenager decided to talk to him.

The applicant appraised/assessed by the supervisor was not right for the job.

The pitcher appraised/assessed by the scout was offered a spot on the team.

Appendix B: Mean fixation times (and standard deviations) in milliseconds on prime and target sentences at the Verb, By-phrase, and Post-target Regions for the first-pass time and total time reading measures

		First-pass Time (ms)			Total Time (ms)		
		Verb Region	**By-phrase Region**	**Post-target Region**	**Verb Region**	**By-phrase Region**	**Post-target Region**
Session 1 Untrained	Primes	357 (180)	580 (291)	563 (342)	501 (298)	770 (391)	592 (346)
	Targets	366 (177)	573 (276)	563 (342)	489 (288)	729 (355)	678 (386)
Trained	Primes	346 (166)	591 (308)	488 (280)	470 (256)	762 (405)	605 (348)
	Targets	355 (171)	570 (300)	486 (273)	455 (254)	714 (397)	589 (342)
Session 2 Untrained	Primes	360 (165)	584 (299)	437 (246)	463 (262)	733 (384)	530 (309)
	Targets	341 (159)	599 (283)	457 (275)	410 (234)	702 (373)	537 (333)
Trained	Primes	360 (158)	574 (312)	467 (232)	459 (259)	702 (398)	550 (307)
	Targets	359 (165)	553 (286)	441 (226)	447 (263)	655 (367)	523 (289)
Session 3 Untrained	Primes	352 (174)	580 (287)	444 (228)	441 (261)	698 (362)	522 (278)
	Targets	336 (167)	586 (311)	456 (254)	404 (236)	679 (370)	518 (289)
Trained	Primes	363 (164)	597 (285)	398 (201)	435 (244)	696 (358)	453 (239)
	Targets	357 (169)	586 (270)	407 (230)	431 (250)	670 (334)	465 (294)
Session 4 Untrained	Primes	360 (170)	567 (297)	433 (226)	441 (244)	682 (366)	501 (277)
	Targets	330 (158)	545 (288)	424 (228)	392 (233)	649 (357)	495 (290)
Trained	Primes	362 (168)	547 (265)	470 (256)	440 (247)	652 (349)	552 (321)
	Targets	354 (163)	529 (263)	463 (243)	405 (221)	594 (308)	528 (286)
Session 5 Untrained	Primes	356 (174)	556 (292)	428 (225)	426 (246)	655 (364)	492 (281)
	Targets	344 (170)	536 (297)	414 (221)	396 (240)	606 (341)	459 (243)
Trained	Primes	356 (178)	578 (272)	450 (265)	426 (245)	680 (332)	508 (309)
	Targets	336 (154)	566 (292)	422 (244)	391 (224)	633 (337)	487 (299)

Highlights

- Decreases in fixation times across study sessions indicated learning of structure.
- Lexically-mediated priming effects were also observed at the target sentences.
- Lexically-mediated priming was found to be independent from the learning effects.
- Consistent with a dual mechanism account of syntactic priming in comprehension.

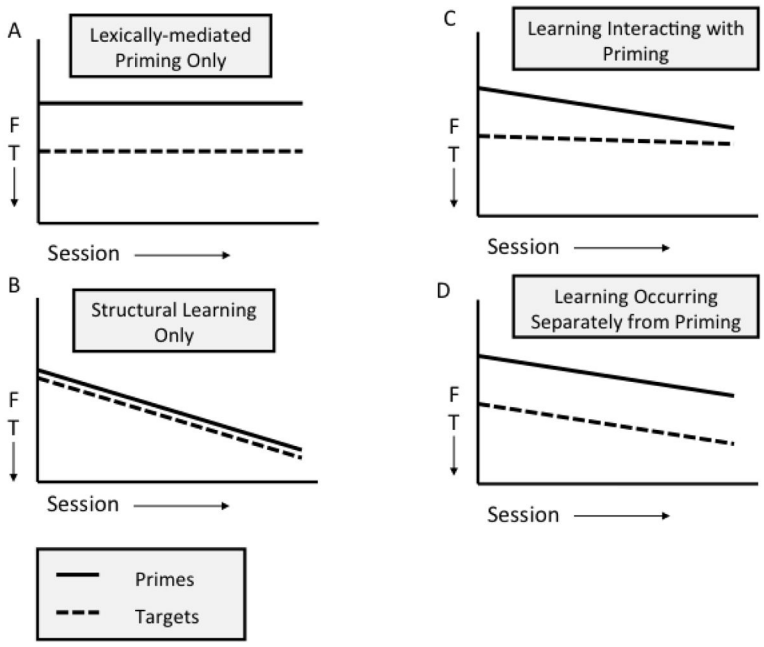

Figure 1.

Possible changes in fixation times (FT) across sessions (solid lines are primes, dotted lines are targets): panel A depicts trial-to-trial priming only, that is consistent across all five sessions; panel B depicts no trial-to-trial priming, but learning of structure across sessions; Panel C depicts both learning of structure and trial-to-trial priming, and those effects interacting (as would be predicted with shared sources of facilitation); and panel D depicts both learning and trial-to-trial priming, but no interaction between the two (as would be predicted by separate sources of facilitation).

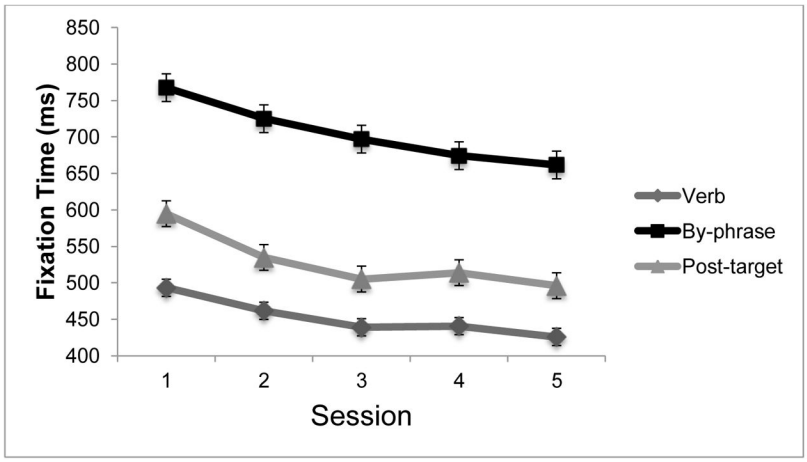

Figure 2.

Mean total fixation times on prime sentences at the Verb, By-phrase, and Post-target regions, across the five training sessions. Error bars represent standard errors.

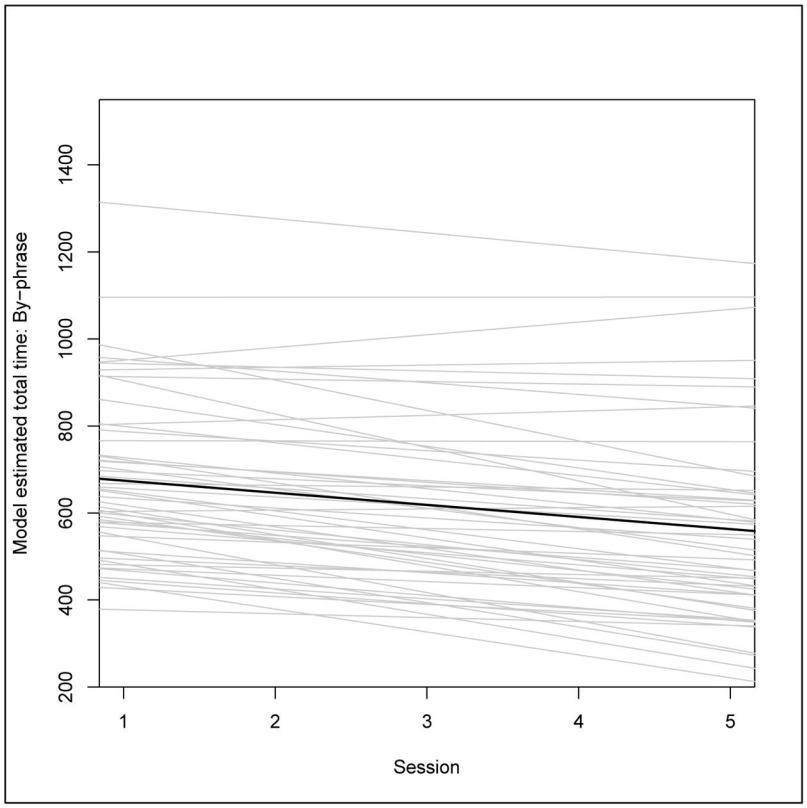

Figure 3.

Model estimated total fixation times for prime sentences at the By-phrase region across the five study sessions. Grey lines indicate individual participant intercepts and slopes for the Session variable, and the black line indicates the overall estimated fixed effect of the Session variable.

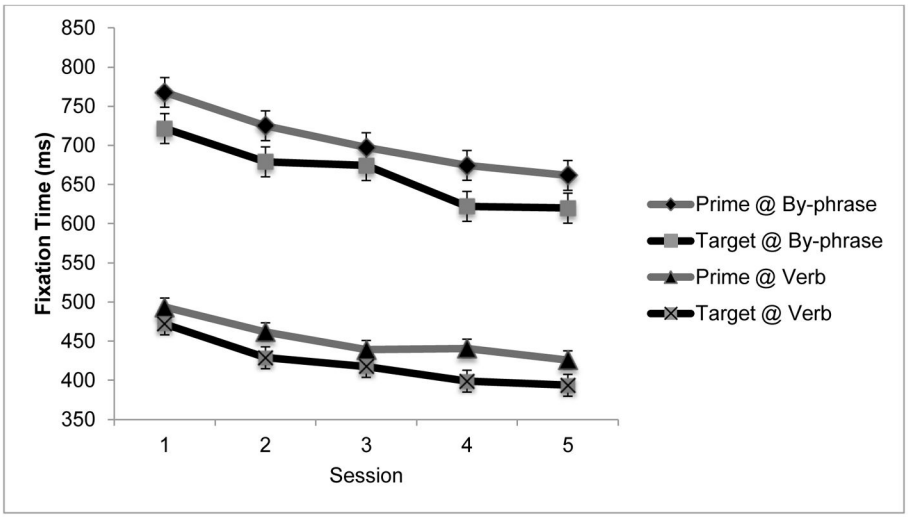

Figure 4.

Mean total fixation times at the Verb and By-phrase regions of the prime and target sentences, across the five training sessions. Error bars represent standard errors.

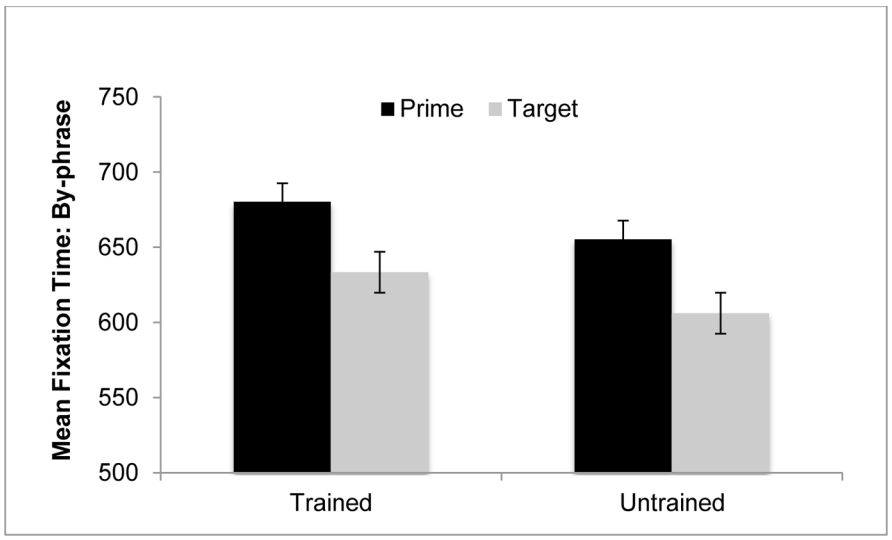

Figure 5.

Mean total fixation times at the By-phrase region of reduced-relative primes and targets during Session Five. “Trained” indicates sentences containing verbs that were present in the structure in all five sessions, while “Untrained” indicates sentences with verbs that had not appeared in the structure in previous sessions.

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Table 1

Model estimates of first-pass and total fixation times at the Verb, By-phrase, and Post-target regions of the prime sentences. Models included centered fixed effects of Session (1–5), Training (Trained vs. Untrained), Item Order (trial position of a sentence in a given session), and the interaction between Session and Training. Simultaneous random intercepts of participant and item identity were included, and random slopes were included as model convergence allowed (exact random effect structure is included in the far left column).

Learning Model Results							
		Time Measure (ms)					
	Coefficient	**First-Pass Time**			**Total Time**		
Verb Region		**Estimate**	**S.E.**	**t-value**	**Estimate**	**S.E.**	**t-value**
Models included random intercepts for all predictors and (participant) random slopes for all but Item Order.	Intercept	354.15	9.23	38.36*	446.37	15.81	28.23*
	Session	0.28	1.92	0.15	−15.96	3.59	−4.45*
	Training	0.26	5.28	0.050	−9.58	8.42	−1.14
	Item Order	−0.015	0.041	−0.37	−0.20	0.065	−3.12*
	Session x Training	1.66	3.73	0.44	5.85	5.89	0.99
By-Phrase Region							
Models included random intercepts for all predictors and (participant) random slopes for all but Item Order.	Intercept	571.48	18.90	30.23*	702.10	28.00	25.08*
	Session	−6.91	4.56	−1.52	−27.83	5.58	−4.99*
	Training	2.37	12.06	0.20	−12.24	13.92	−0.88
	Item Order	−0.21	0.093	−2.31*	−.39	0.11	−3.59*
	Session x Training	0.52	8.40	0.062	4.93	9.86	0.50
Post-target Region							
Models included random intercepts for all predictors and (participant) random slopes for all but Item Order.	Intercept	438.25	14.01	31.28*	520.91	19.02	27.39*
	Session	−8.07	4.47	−1.81	−22.33	4.88	−4.58*
	Training	12.60	13.72	0.92	2.47	14.39	0.17
	Item Order	−0.052	0.11	−0.49	−0.20	0.11	−1.82
	Session x Training	−0.34	9.60	−0.035	−0.40	10.03	−0.040

* indicates t-value > 2.0, and p-value < .05

Table 2

Model estimates of first-pass and total fixation times at the Verb, By-phrase, and Post-target regions of the prime and target sentences. Models included centered fixed effects of Sentence Position (Prime vs. Target) Session (1–5), Training (Trained vs. Untrained), Item Order (trial position of a sentence in a given session), and all interactions between Sentence Position, Session, and Training. Simultaneous random intercepts of participant and item identity were included, and random slopes were included as model convergence allowed (exact random effect structure is included in the far left column).

Priming Model Results							
		Time Measure (ms)					
	Coefficient	**First-Pass Time**			**Total Time**		
Verb Region		**Estimate**	**S.E.**	**t-value**	**Estimate**	**S.E.**	**t-value**
Total time model includes random intercepts by items and participants and random slopes for the by-item effect of Position and by-participant effects of Position, Training, Session, Position x Training, and Position x Session. First-pass model included random intercepts and random slopes for the effect of Sentence Position.	Intercept	350.76	8.81	39.82	435.76	14.71	29.63*
	Sentence Position	−10.64	4.36	−2.44*	−30.23	6.60	−4.58*
	Training	3.15	4.08	0.77	−4.08	7.04	−0.58
	Session	−1.33	1.34	−0.99	−16.57	3.39	−4.88*
	Item Order	−0.021	0.034	−0.62	−0.19	0.056	−3.37*
	Position x Training	8.61	8.18	1.05	16.69	11.57	1.44
	Training x Session	1.58	2.89	0.55	4.37	4.84	0.90
	Position x Session	−5.47	2.85	−1.92	−3.50	4.02	−0.87
	Position x Training x Session	−0.66	5.78	−0.11	−4.96	7.95	−0.62
By-Phrase Region							
Total time model includes random intercepts by items and participants and random slopes for the by-item effect of Position and by-participant effects of Position, Training, Session, Position x Training, and Position x Session. First-pass model includes random intercepts and by-participant random slopes for Session and Training.	Intercept	568.73	18.77	30.31*	686.39	27.00	25.42*
	Sentence Position	−10.34	9.01	−1.15	−45.57	8.17	−5.58*
	Training	−1.07	9.01	−0.12	−12.25	13.21	−0.93
	Session	−7.83	4.11	−1.91	−26.61	5.46	−4.87*
	Item Order	−0.18	0.074	−2.41*	−0.38	0.10	−3.63*
	Position x Training	−10.95	18.22	−0.60	0.40	12.09	0.033
	Training x Session	3.43	6.38	0.54	3.74	9.29	0.40
	Position x Session	−3.00	6.36	−0.47	2.07	4.64	0.45

Priming Model Results							
		Time Measure (ms)					
	Coefficient	First-Pass Time			Total Time		
Verb Region		**Estimate**	**S.E.**	**t-value**	**Estimate**	**S.E.**	**t-value**
	Position x Training x Session	8.28	12.87	0.64	−3.33	8.48	−0.39
Post-target Region							
Total time model includes random intercepts by items and participants and random slopes for the by-item effect of Position and by-participant effects of Training, Session, Position x Training, and Position x Session. First-pass model included random intercepts and by-participant random slopes for the effects of Sentence Position and Session.	Intercept	442.82	13.73	32.26*	517.73	19.17	27.00*
	Sentence Position	10.16	11.09	0.92	−11.47	5.35	−2.14*
	Training	2.01	10.62	0.19	0.39	14.20	0.028
	Session	−13.89	3.84	−3.62*	−22.13	5.02	−4.41*
	Item Order	−0.057	0.088	−0.65	−0.21	0.11	−1.90
	Position x Training	−33.16	21.48	−1.54	−6.80	10.00	−0.68
	Training x Session	7.22	7.52	0.96	0.056	9.79	0.006
	Position x Session	−17.49	7.51	−2.33*	0.75	3.95	0.19
	Position x Training x Session	22.48	15.18	1.48	1.23	6.83	0.18

* indicates t-value > 2.0, and p-value < .05