Persistent Structural Priming during Online Second Language Comprehension

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Abstract

We report two self-paced reading experiments investigating the longevity of structural priming effects in comprehending reduced relative clauses among adult Chinese-speaking learners of English. Experiment 1 showed that structural priming occurred both when prime and target sentences were immediately adjacent and when they were separated by one or two filler sentences of unrelated structures. Moreover, the magnitude of priming effect held constant across different lag conditions. Experiment 2 replicated the persistent priming effect, and ruled out the possibility that the effect was due to verb repetition priming. Taken together, the current results suggest that recent experience with a given structure can have relatively long-lived facilitation effect upon the language processing system in L2 learners. As such, structural priming may serve as a learning mechanism for second language speakers.

Keywords: structural priming, learning mechanism, L2 comprehension

Comprehending a sentence involves identifying its syntactic structure so that its meaning can be interpreted. For adult native speakers, syntactic processing is guided by their mature grasp of the language's syntax. In contrast, second language (L2) learners begin with a much less complete syntactic repertoire, which they gradually increase through explicit and (possibly) implicit learning. The current study investigates a possible implicit learning mechanism for L2 learners: structural priming during sentence comprehension, such that experiencing a given syntactic structure in a second language influences later comprehension of that structure. Crucially, such a priming effect will be most relevant for L2 acquisition if it is long-lived.

Structural priming is a well-established phenomenon in both adult native speakers and bilinguals, and occurs in both production and comprehension modalities (see Pickering & Ferreira, 2008, for a review). For instance, people read a reduced relative clause sentence (e.g., *The defendant examined by the lawyer turned out to be unreliable*) faster if they have previously read a sentence of a similar structure (e.g., *The engineer examined by the board passed with flying colors*). The facilitation has been argued to arise from implicit adaptation of syntactic processing mechanisms, because it persists across intervening sentences (e.g., Bock & Griffin, 2000; Chang, Dell, & Bock, 2006; Dell & Chang, 2014; Fine & Jaeger, 2013). Further, Chang et al. (2006) argued that structural priming in the production modality occurs via the same implicit learning mechanism through which young children acquire their first language. This claim was extended to include L2 acquisition in Janciauskas and Chang (2017), demonstrating that the Chang et al. model of L1 implicit learning in adults and children could also predict knowledge of English syntax in Korean L2 learners at different ages of acquisition, levels of English exposure, and for different grammatical rules.

The degree to which adults can make use of implicit learning of syntax is a matter of debate. On the one hand, it has been argued that, for adult L2 learners, explicit instruction is more effective than implicit learning (e.g., Norris & Ortega, 2000; Spada & Tomita, 2010); some even claim that after puberty only explicit language learning is possible (Bley-Vroman, 1990, 2009; DeKeyser, 2003; DeKeyser & Larson-Hall, 2005). On the other hand, more recent research has suggested that the L1 syntactic system is constantly being reshaped by incoming linguistic input throughout adulthood, via implicit learning mechanisms (e.g., Fine, Jaeger, Farmer, & Qian, 2013; Fraundorf & Jaeger, 2016; Kaschak & Glenberg, 2004). Somewhere in between is Janciauskas and Chang's (2017) model of L2 acquisition, in which learners have two distinct mechanisms, a syntactic learning mechanism and a

lexical learning mechanism, which have different learning trajectories. In their model, the syntactic learning rates were maximal during the first ten years of life, but decreased to zero by age 16. In contrast, the lexical learning mechanism did not decline with age, which allowed late learners (after age 16) to pick up some structural regularities in the second language. In sum, L2 learners clearly can acquire new syntactic constructions/rules, but it isn't clear how much of this is due to implicit learning, and the degree to which the implicit learning is lexicalized.

Crucially, prior experimental work demonstrates that adult L2 learners are susceptible to structural priming during L2 production (e.g., McDonough, 2006; Shin & Christianson, 2012) and that such effects can be quite long-lived, persisting two to four weeks after the initial priming session (McDonough & Chaikitmongkol, 2010; McDonough & Kim, 2009).The emerging picture is that structural priming is an important implicit learning mechanism that may be relevant for acquisition of L2 syntax. However, the most direct evidence so far comes from Janciauskas and Chang (2017), who were modeling structural priming in the production modality. This focus on production is consistent with the experimental literature – research has been sparse as to whether learners can also implicitly learn syntactic structures from comprehension. Because L2 learning (especially in the foreign language learning settings) is mainly accomplished via listening and reading, it is important to explore whether L2 learners implicitly learn syntactic structures from comprehending sentences.

The present study shifts the focus to L2 structural priming in comprehension, by examining whether exposure to a difficult (garden-path) structure can facilitate subsequent processing of that structure, and more importantly, whether this effect is transient or persists across multiple sentences. We investigated the online processing of English sentences containing a reduced relative clause (e.g., *The defendant examined by the lawyer turned out to be unreliable*), a structure that has received much attention in L1 comprehension priming research. Prior results show that the processing of relative clauses is susceptible to structural priming, both when the prime and target sentences are immediately adjacent (Ledoux, Traxler, & Swaab, 2007; Tooley & Bock, 2014; Tooley, Swaab, Boudewyn, Zirnstein, & Traxler, 2014; Tooley, Traxler, & Swaab, 2009; Traxler & Tooley, 2008; Traxler, Tooley, & Pickering, 2014) and when the prime and target are separated by one or three filler sentences of unrelated structures (e.g., Tooley, et al., 2014).

Priming of relative clauses in L1 comprehension seems to be dependent upon verb repetition between the prime and target sentences (e.g., Ledoux et al., 2007; Tooley et al, 2009; Traxler &

Tooley, 2008; Traxler et al., 2014; though see Tooley & Bock, 2014, for demonstration of lexically independent, trial-to-trial priming of relative clauses[1]). For instance, using ERP and eye-tracking measures, Tooley and colleagues (2009) had participants read pairs of sentences each containing a reduced relative clause, with either the verb repeated within the pair (e.g., *examined* in sentences 1 and 2) or not (e.g., *examined* vs. *reviewed* in 1 and 3). Participants experienced less processing difficulty reading the target sentence (compared with the prime) when the prime and target contained the same verb, but not when prime and target contained semantically similar verbs (*examined*, *reviewed*).

> 1. The defendant *examined* by the lawyer turned out to be unreliable.
>
> 2. The engineer *examined* by the board passed with flying colors.
>
> 3. The engineer *reviewed* by the board passed with flying colors.

Tooley et al. (2014) replicated this pattern, even when prime and target sentences were not adjacent but separated by one or three unrelated filler sentences. Moreover, the strength of the priming effect did not decline over the lag, suggesting that experience with a given structure during comprehension may assist learning of that structure.

A recent study found that exposure to relative clause sentences can facilitate subsequent processing in L2 comprehension. Using a word-by-word, self-paced moving-window display, Wei and colleagues (2017) investigated online comprehension priming of reduced relative clauses (in sentences like 1-3) in Chinese L2 learners of English. When considering L2 learning of relative clauses, Chinese-speaking learners of English are especially interesting because the predominant word order in Chinese is SVO, the same as English, but the word order in relative clauses is very different[2]. In Wei et al. (2017), each prime sentence was immediately followed by a target sentence. Robust structural priming occurred when the prime and target sentences contained the same verb, but no priming occurred when

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[1] The reason that Tooley and Bock (2014) observed lexically independent priming of relative clauses in comprehension may be due to the fact that their participants first read the prime sentence presented in rapid serial visual presentation (RSVP) and then read it in a self-paced, moving window display. That is, each prime sentence was presented twice before the target, which may have enhanced the abstract, trial-to-trial priming.

[2] English relative clauses are head-initial, with the relative clause following the head noun (e.g., *the girl who is standing on the balcony*), whereas relative clauses in Chinese are head-final, with the relative clause preceding the head noun (e.g., *zhanzai yangtai shang de nage nvhai*, standing on the balcony *de*-relativizer the girl).

prime and target contained different verbs. Hence, online comprehension priming of L2 reduced relative clause sentences appears to be dependent upon verb repetition, in keeping with prior research on English native speakers (Ledoux et al., 2007; Tooley et al., 2009; Tooley et al., 2014; Traxler et al., 2014; Traxler & Tooley, 2008; cf. Tooley & Bock, 2014).

Given that Wei et al. (2017) investigated priming only in the immediately adjacent condition, it remains to be tested whether the observed priming effect would persist over intervening sentences. If the structural priming doesn't persist over even a few sentences, it is unlikely to play a role in L2 acquisition. To examine the longevity of priming effects, we manipulated the lag between prime and target sentences such that the prime and target were either immediately adjacent, or were separated by one or two unrelated filler sentences, as in Tooley and colleagues (2014, Experiment 2). On the basis of prior results (e.g., Tooley, et al., 2009; Wei, et al., 2017), we expected to observe faster reading times on the disambiguating region of target sentences (e.g., "by the lawyer" in (1)) as compared with the same region of prime sentences in Experiment 1. In Experiment 2, we manipulated whether prime sentences had main clause or reduced relative clause structures and we expected the disambiguating region of the relative clause target sentence to be read faster after relative clause primes compared with main clause primes. In both experiments, if the priming effect is relatively long-lived, we should observe the structural priming effect when the prime and target are separated by unrelated fillers, with little or no diminishing in the size of the priming effects. However, if priming during online L2 comprehension turns out to be short-lived, then the priming effect might be severely reduced or disappear completely when prime and the target are separated by unrelated fillers.

Experiment 1

We investigated priming of the reduced relative clause sentences in three conditions. In the first condition, the prime and target sentences were immediately adjacent (Lag 0 condition). In the second condition, one unrelated filler sentence separated the prime sentence from the target (Lag 1 condition). And in the third condition, two unrelated fillers intervened between the prime and the target sentences (Lag 2 condition).

Method

Participants. Thirty-six undergraduates from Xi'an Jiaotong University were paid to participate. All participants were native speakers of Chinese and were learning English as their second language. Their average age was 19 years (range = 18-20), and they had received formal English instruction in

China for an average of 6.5 years (6 years at middle school starting around the age of 12, plus half a year at university) at the time of the current study. None of them reported to have lived or studied in an English-speaking country. Their vision or corrected vision was normal and reported no reading difficulties.

Items. Seventy-two English reduced relative clauses were selected from a larger set used in a prior study on structural priming in L1 comprehension (Tooley, et al., 2009; see Appendix for a complete list of the sentences). Some of the sentences were adapted (e.g., by replacing a difficult, low-frequency word with a high-frequency one) in order to ensure that all sentences could be understood by our participants. We created 36 prime-target pairs out of the 72 sentences; in each pair, the prime and target shared the same verb within the relative clause. As shown in Table 1, a prime sentence was immediately followed by a target sentence (the Lag 0 condition), or was separated from the target by one (the Lag 1 condition) or two filler sentences (the Lag 2 condition).

---Insert Table 1 about here---

There were six experimental lists, created by crossing sentence type (prime vs. target) with lag conditions (Lag 0 vs. Lag 1 vs. Lag 2). Each of the 72 relative clause sentences was rotated across six lists. Each sentence appeared as a prime on three lists, and as a target on the other three lists. This counterbalancing allowed for the comparison across prime and target items using the exact same sentences. Across lists, each prime-target pair presented with no intervening sentence in one list was presented with one intervening sentence in another list, and with two intervening sentences in a third list. The items were presented to participants in a fixed, randomized order, so that all participants read a given list in the same order. Each participant read any particular sentence only once.

In addition, there were 144 filler sentences of unrelated structures, 36 of which served as placeholder sentences in Lag 1 and Lag 2 conditions (12 for Lag 1 condition prime-target pairs, and 24 for Lag 2 condition). The fillers sentences consisted of various syntactic structures, including *there-be* construction (e.g., *There is a wooden bridge over the river*), simple transitive/intransitive sentences (e.g., *Professor Wilson was talking about the consequence of the recent election*), and conjoined clause

sentences (e.g., *Although I admire her courage, I don't think she acted wisely*). None of the filler sentences involved the relative clause construction, and there was no verb overlap between the fillers and prime-target pairs. There were three filler sentences separating one prime-target pair from the next.

Procedure. The experiment was conducted using E-Prime. Participants were tested individually and were randomly assigned to an experimental list. They read sentences in a word-by-word, self-paced moving window display (Just, Carpenter, & Woolley, 1982). At the beginning of each trial, the sentence appeared on the screen with each word covered by a single underline. Participants pressed "Enter" to view each consecutive word. At each press, the currently viewed word reverted to an underline as the next word was uncovered. Forty-eight sentences were followed by a yes-no comprehension question, distributed among 12 target sentences and 36 non-placeholder fillers. Participants received no feedback on their responses. The experiment began with a practice session consisting of six additional filler sentences.

Scoring. The estimates of priming effects were based upon measuring participants' reading times on sentences like *The speaker selected by the group would be perfect for the program* when it appeared as a prime versus when it appeared as a target. Although the sentences were displayed one word at a time, following previous studies of a similar design (e.g., Fine & Jaeger, 2016; Tooley, et al., 2014), we segmented sentences into scoring regions for the purposes of analysis. For multi-word scoring regions, reading times were summed across the words. Three scoring regions were analyzed. The *Verb* region consisted of only the verb in the relative clause (e.g., *selected* in Table 1). The *Disambiguating By-phrase* region consisted of the syntactically disambiguating *by*-phrase (e.g., *by the group*). The *by*-phase was treated as a whole because it is a linguistically defined unit that has been used in previous studies on this sentence type (e.g., Tooley, et al., 2014; Tooley, et al., 2009; Wei, et al., 2017). The *Post-disambiguation* region consisted of the two words immediately following the *by*-phrase region (e.g., *would be*). The Post-disambiguation region was included to capture potential spillover effects. If priming occurred, we would expect to observe repetition priming effects at the verb and syntactic priming effects in the disambiguating *by*-phrase region.

Results

One participant was excluded due to poor performance in answering the comprehension questions (with an accuracy rate lower than 80%). For the remaining participants, the average accuracy on the comprehension questions were 89% (SD = 5%). For the RTs on each word, we first excluded 77 (i.e.,

3%) of the experimental trials on which participants answered comprehension questions incorrectly. Next, we replaced RTs for individual words that were less than 100 ms with the participant grand mean and then replaced RTs for any individual words that were three standard deviations away from the participant grand mean with the cutoff values. This affected a further 2% of the data points. As discussed above, we then used these individual word RTs to compute reading times for the three critical regions. Figure 1 presents mean reading times under each lag condition from the onset of the sentence till the second word following disambiguation.

---Insert Figure 1 about here---

We used linear mixed effects (LME) modeling (the lme4 package, version 1.1.13) to analyze trial-level RTs for each reading region, taking into account both by-participant and by-item random effects. Following recent suggestions (Bates, Kliegl, Vasishth, & Baayen, 2015; Matuschek, Kliegl, Vasishth, Baayen, & Bates, 2017), we determined the best fitting random effect structure using forward model comparison[3]. The model included all the fixed effects: sentence type (contrast-coded: prime sentence = 0.5, target sentence = -0.5), lag condition (as a continuous variable) and their interaction. We next used forward model comparison to determine the best-fitting random effect structure. A random slope was kept in the random effect structure if its addition would increase the model fit. Following Matuschek et al. (2017), we set the significance level for model selection at 0.2 rather than 0.05.

As can be seen in Figure 1 and Table 2, there is a similar pattern across the three reading regions. For the verb region, there was a significant effect of sentence type, with the target verb read faster than the prime verb. Lag did not produce a significant effect. The interaction between sentence type and lag did not reach significance, suggesting that the reading time benefit for the verb in the target compared to the prime sentence remained constant across different lag conditions. For the disambiguating *by*-phrase, the significant effect of sentence type suggested that structural priming occurred in this region; that is, a sentence was read faster in this region if it served as a target sentence than as a prime

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[3] We opted to use forward model comparison because backward model comparison often resulted in non-convergence.

sentence[4]. Lag did not produce a significant effect, and more critically did not interact with sentence type. This latter result suggests that the priming effect did not vary as a function of the lag between the prime and the target. For the two words immediately following disambiguation, sentence type produced a marginally significant effect, with targets again read faster than primes. Lag did not produce a significant effect nor did it interact with sentence type.

--- Insert Table 2 about here---

We were interested in testing whether structural priming, if observed, was modulated by the lag condition; we noted, however, that not much could be said of a null effect within the null hypothesis significance testing approach. Thus, to further examine the null interaction between sentence type and lag condition, we turned to Bayes factor (BF) analysis, which calculated the likelihood ratio (on the basis of the observed data) of the null hypothesis against the alternative hypothesis (BF_{01}) or of the alternative hypothesis against the null hypothesis (BF_{10}) (Jeffreys, 1998; Kass & Raftery, 1995; Wagenmakers, 2007). Following Wagenmakers (2007), we used the Bayesian Information Criterion (BIC) in the LME models of the alternative hypothesis (with all the fixed effects and the best-fitting random effect structure) and of the null hypothesis (i.e. with the sentence type by lag condition interaction removed from the fixed effect structure) to calculate BFs (i.e. $BF = e^{\Delta BIC/2}$). The null hypothesis concerning the interaction (i.e. lag did *not* modulate the effect of sentence type) was respectively about 33, 33 and 55 times more likely than the alternative hypothesis (i.e. lag modulated the effect of sentence type) in the three regions (Verb, $BF_{01} = 33.1$; By-phrase, $BF_{01} = 33.1$; Post, $BF_{01} = 54.6$).

We also conducted an LME analysis to test whether the priming effect was modulated by trial order; that is, whether the magnitude of priming effect linearly changed as the experiment progressed. As prime-target lag did not have any effect, we discarded this predictor in the model and included sentence type, trial order (log-transformed) and their interaction as fixed effects in the model. Across the three regions, sentence type had a significant effect (faster reading for the target than the prime

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[4] Though it is possible that the sentence type effect here is due to the repetition of the words "by the", excluding the words "by the" from this region did not change the result.

sentence) at the Verb (β = 28.8, SE = 7.1, t(33.3) = 4.08, $p < .001$) and By-phrase (β = 31.1, SE = 8.2, t(32.7) = 3.77, $p < .001$), though not in the post-disambiguation region (β = 7.8, SE = 5.1, t(303.0) = 1.5, $p = .124$). Trial order had a significant effect in all three regions (Verb: β = -65.4, SE = 12.1, t(70.8) = -5.40, $p < .001$; By-phrase: β = -126.1, SE = 12.9, t(68.9) = -9.75, $p < .001$; Post: β = -78.6, SE = 14.4, t(80.9) = -5.45, $p < .001$), with quicker reading time as the experiment progressed. Crucially, however, there was no significant interaction between sentence type and trial order in any region (Verb: β = -6.7, SE = 5.4, t(2328.0) = -1.23, $p = .217$; By-phrase: β = 4.7, SE = 6.9, t(2309.1) = 0.68, $p = .494$; Post: β = -2.6, SE = 5.5, t(74.5) = -0.48, $p = .636$). These latter findings suggest that the strength of structural priming effect did not change across the experiment. We will return to this issue in the General Discussion.

Discussion

For the three critical regions, participants read the target sentences faster than the prime sentences. The effect of sentence type at the verb probably reflects lexical repetition of the verb. Thus, the faster reading times for the target sentences during the disambiguating *by*-phrase and the post-disambiguation region (marginally) are important for demonstrating structural priming. The observed data pattern replicated the finding in Wei et al. (2017), showing that priming occurred in online L2 comprehension (at least) when the target and the prime sentences shared the same verb within the relative clause. More importantly, the finding that the priming effect was constant across different lags (as indicated by the non-significant interaction between sentence type and lag condition, bolstered by the BF analyses) further suggests that the priming effect is not confined just to an immediately following sentence but instead persists over time and intervening sentences of unrelated structures[5]. To our knowledge, this constitutes the first demonstration of persistent structural priming during online L2 comprehension.

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[5] A possibility is the lack of a lag modulation of the priming effect was due to insufficient power in the current experiment (and indeed also in Experiment 2). As no previous studies similar to ours (structural priming in self-paced reading) have reported a prime type by lag interaction or a relevant effect size for such an interaction, there is no way to estimate the effect size of the critical interaction in our study. Instead, we adopted a relatively conservative effect size (d = 0.4), assuming that such an effect exists. Using the power analysis toolkit provided by Westfall, Kenny, and Judd (2014) (https://jakewestfall.shinyapps.io/crossedpower/) and their proposed sizes of variance components, we showed that, for the counter-balanced design we had in our study and under the assumption of relatively small effect size d = 0.4, our Experiment 1 (36 participants and 72 experimental items)

Experiment 2

Given that the prime and target sentences in Experiment 1 involved the same verb (along with the same syntactic structure), it is likely that some of the priming effects on the target sentence reflect lexical repetition rather than structural priming. This is almost certainly the case on the verb, but it is possible that the effect in the disambiguating region was also at least partially a carry-over effect from the verb repetition. To test this possibility, we conducted Experiment 2, which included both main-clause and reduced relative clause prime conditions. Target sentences always contained reduced relative clauses. The prime and target sentences again shared the same verb, because prior research found that verb repetition was necessary for relative clause priming (Wei, et al., 2017). If the effect observed in Experiment 1 is actually due to lexical repetition priming, then both types of prime sentences should exhibit priming effects; however, if the effect observed in Experiment 1 reflects real structural priming, then only the reduced relative clause primes should elicit priming effects.

Experiment 2 used the same procedure and materials as Experiment 1, except that half of the primes consisted of main clause sentences. In addition, only Lag 0 and Lag 2 were included in this experiment[6].

Method

Participants. Forty-eight new participants (mean age = 19, ranging from 18 – 20) from the same population as in Experiment 1 were paid to participate.

Items. The same 72 reduced relative clauses used in Experiment 1 were employed in Experiment 2. These sentences constituted 36 prime-target pairs. In addition, 36 main clause primes (like 4) were derived from the reduced relative clause primes, constituting another 36 prime-target pairs.

4. The group selected the speaker who would be perfect for the program.

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had 85% of statistical power and our Experiment 2 (48 participants and 72 experimental items) had 91% of statistical power to detect the interaction if it is real. Hence, we believe that our experiments were sufficiently powered.

[6] The Lag 1 condition was not included because the priming effect was robust under this condition in Experiment 1, and excluding this condition allows for more items within each cell.

12

Both the main clause and the reduced relative clause primes used the same verb as the target sentence with which they were paired. Each prime sentence was either immediately followed by a target sentence (Lag 0), or was separated by two unrelated fillers from the target (Lag 2).

There were four experimental lists, created by crossing prime type (main clause vs. reduced relative clause) with lag (Lag 0 vs. Lag 2). Each target sentence was paired with a main clause prime on two lists, and with a reduced relative clause prime on the other two lists. Across lists, each prime-target pair presented with no intervening sentence in one list was presented with two intervening sentences in another list. As in Experiment 1, the items were presented to participants in a fixed, randomized order, so that all participants read a given list in the same order. Each participant read any particular sentence only once. The same 144 filler sentences from Experiment 1 were used in Experiment 2, with three fillers separating one prime-target pair from the next.

Procedure and Scoring. These were the same as in Experiment 1.

Results

One participant was excluded from further analyses for having a low accuracy rate in answering the comprehension questions (78%). After exclusion, the average by-participants comprehension accuracy was 92% (SD = 5%). We further excluded 52 experimental trials (3%) where the comprehension question was not answered correctly. Next, we replaced outliers using the method in Experiment 1, affecting a further 2% of all the data points. Figure 2 presents mean reading times under each lag condition from the onset of the target sentence till the second word following disambiguation.

---Insert Figure 2 about here ---

As in Experiment 1, we conducted LME analyses on the reading times in the three critical regions, using prime type (contrast-coded: relative clause prime = -0.5, main clause prime = 0.5), lag condition (contrast-coded: lag 0 = -0.5, lag 2 = 0.5) and their interaction as fixed effects. A summary of the modeling results is given in Table 3.

At the verb, there was no effect of prime type, lag condition or their interaction. In the disambiguating *by*-phrase, there was a significant main effect of prime type, with faster reading times if the relative clause target followed a relative clause prime compared with a main clause prime. Lag

condition did not produce a significant effect, nor did it modulate the effect of prime type. In the post-disambiguation region, none of the predictors produced a significant effect.

As in Experiment 1, the null interaction between prime type and lag condition (especially for the disambiguating *by*-phrase) was not very informative, so we conducted BF analyses on these interactions. Across all three regions, the null hypothesis (i.e. lag did not modulate the effect of prime type) was much more likely than the alternative hypothesis (i.e. lag modulated the effect of prime type) (BF_{01} was 20.1, 33.1 and 33.1 respectively for the three critical regions).

In addition, we also tested whether trial order modulated priming effects by including prime type, trial order (log-transformed) and their interaction in LME models. Prime type had a significant effect in the disambiguating *by*-phrase (β = 19.2, *SE* = 8.2, *t*(32.8) = 2.34, *p* = .026) though not at the verb (β = 11.8, *SE* = 8.3, *t*(53.9) = 1.43, *p* = .159) or the post-disambiguation region (β = 5.13, *SE* = 6.20, *t*(33.3) = 0.83, *p* = .414). Trial order had a significant effect across all three regions, with reading times decreasing as the experiment progressed (Verb: β = -66.3, *SE* = 17.0, *t*(36.0) = -3.89, *p* < .001; By-phrase: β = -103.7, *SE* = 16.6, *t*(45.4) = -6.23, *p* < .001; Post: β = -53.3, *SE* = 10.9, *t*(34.0) = -4.87, *p* < .001). More importantly, there was no significant interaction between sentence type and trial order in any region (Verb: β = -3.2, *SE* = 8.5, *t*(40.6) = -0.38, *p* = .705; By-phrase: β = 13.0, *SE* = 8.3, *t*(34.4) = 1.57, *p* = .125; Post: β = -6.5, *SE* = 7.8, *t*(35.5) = -0.83, *p* = .412). These latter findings suggest that the size of structural priming effect remained constant across the experiment.

---Insert Table 3 about here---

Discussion

Reading times on the disambiguating *by*-phrase of the target sentence were affected by the prime sentence structure: Target sentences were read faster following the relative clause primes than following the main clause primes. Crucially, the verb was repeated across both types of prime; thus the observed priming effect should be attributed to structural repetition, not verb repetition. As in Experiment 1, the priming effect did not vary as a function of the lag between prime and target: Target sentences were read faster under the relative clause prime condition both when the prime and target sentences were immediately adjacent and when they were separated by two unrelated filler sentences.

Compared with Experiment 1, the priming effects in Experiment 2 arose a bit later, during the disambiguating *by*-phrase region rather than on the verb itself. Thus, it seems likely that the facilitatory effect at the verb in Experiment 1 was due, at least in part, to lexical repetition priming.

General discussion

We investigated the longevity of structural priming effects during L2 comprehension in two self-paced reading experiments. Both experiments used sentences containing English reduced relative clauses as the target structure. In both experiments, prime and target sentences were either immediately adjacent or were separated by one or two unrelated filler sentences. The prime and target sentences used the same initial verb across both experiments. Experiment 1 showed that structural priming during online L2 comprehension can persist across time and intervening sentences of unrelated structures. This finding was replicated in Experiment 2, which further showed that the effect reflected structural priming rather than (merely) lexical repetition priming.

Taken together with the larger literature on structural priming as implicit learning (e.g., Bock & Griffin, 2000; Chang, et al., 2006; Dell & Chang, 2014; Fine & Jaeger, 2013, 2016), these results suggest that experience with a given structure during online L2 comprehension can have relatively long-lasting learning effects. Moreover, this learning seems to take place tacitly. In the two experiments, participants did not receive any instruction on the syntactic features of the sentences, nor were they explicitly aware of the target structure (as confirmed by a post-experiment interview). Simply reading one instance of the relative clause structure using a particular verb led to priming for a subsequent sentence containing the same verb in the same relative clause structure.

Our findings fit well with lexicalist constraint-based theories of sentence processing (e.g., MacDonald, Pearlmutter, & Seidenberg, 1994) and usage-based accounts of grammar (e.g., Bybee, 2006), according to which grammatical representations are based on one's experience with the language. Such theories predict that the kind of input that L2 learners receive can have substantial impact on their developing language system. English reduced relative clauses may be particularly challenging for the L2 learner, because most English verbs have the same *-ed* form in the simple past and past participle tenses, giving rise to the temporary ambiguity between a main clause and a relative clause interpretation. Experiencing such verbs as past participles within relative clauses may facilitate future processing of reduced relative clauses.

The finding of persistent structural priming during online L2 comprehension is consistent with prior research on English L1 speakers involving the same sentence type and the same comparison between primes and targets as Experiment 1 (e.g., Tooley, et al., 2014). Moreover, the absolute size of the priming effect is comparable to prior L1 results. For example, in Tooley et al.'s Experiment 2, participants showed a 55 ms (729 vs. 784 ms) gain in total reading times at the disambiguating PP region when prime and target were separated by three unrelated fillers, and in the present Experiment 1 participants had a 76 ms (1321 vs. 1397 ms)[7] gain in the Lag 1 condition and 54 ms (1354 vs. 1408 ms) in the Lag 2 condition. This parity of results suggests that similar mechanisms might be involved in L1 and L2 for comprehension priming of relative clauses.

The current findings have implications for second language learning, because structural priming may serve as a learning mechanism for L2 speakers, especially for difficult, infrequent structures such as reduced relative clauses, which are temporarily ambiguous with a main clause alternative. Readers tend to be biased in favor of the main clause structure because of its high frequency and the general imbalance between past tense and past participle forms of specific verbs (Trueswell, Tanenhaus, & Kello, 1993). For the priming effects reported here, the prime and the target shared the same verb[8]. Thus, the observed structural priming may have reflected the enhancement of the connection between a verb and its syntactic alternatives. Such lexicalized structural priming effects appear to be consistent with the lexicalized learning mechanism modeled by Janciauskas and Chang (2017) for L2 acquisition. Recall that their model eliminated the purely syntactic learning mechanism by age 16. Whether purely syntactic implicit learning can occur in L2 acquisition after the age of 16 remains an open question.

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[7] The differences in reading times may be due to the different reading tasks employed in these studies. For instance, Tooley et al.'s Experiment 2 (2014) used eye tracking, while we used self-paced reading. There is evidence that the rate of self-paced reading is about half as fast as that of eye-tracking (Rayner, 1998). In addition, our participants are L2 learners, whose English proficiency is less advanced compared with the L1 speakers employed in Tooley et al.'s study.

[8] Although we didn't include the different-verb condition, a prior study involving similar method and materials as the present study showed that L2 online comprehension priming of relative clause occurred only when the prime and target sentences used the same verb but not otherwise (Wei, et al., 2017).

The experiments reported here did not test, and do not address, the question of whether adult L2 implicit learning includes lexically independent structural priming.

Readers might be tempted to over-interpret the absence of a cumulative priming effect accrued after repeated exposures to the reduced relative clause structure throughout the experiment (cf. Fine & Jaeger, 2016). If such an effect had been observed in our experiments, it would have been based on priming between relative clause sentences with different verbs and thus could have provided evidence for lexically independent priming. We did not observe cumulative priming in either experiment, as evidenced by the lack of an interaction between trial order and the priming effect. This was not surprising, because Wei et al. (2017) and Tooley et al. (2014) failed to detect lexically independent relative clause priming in comprehension of L2 and L1 respectively. The absence of an interaction between trial order and the priming effect does not rule out the possibility of lexically-independent relative clause priming, if the trial-to-trial priming effect was (at least partly) driven by an error-based implicit learning mechanism (Chang, et al., 2006). Given that the reduced relative clause structure occurs quite infrequently, the structure has a low probability and should hence induce a large learning effect. As the experiment progressed, however, participants would have encountered more and more instances of the relative clause structure, increasing its probability and consequently reducing its learning effect, making the priming effect essentially constant. Therefore, while we found no evidence of a cumulative priming effect based on lexically-independent structural priming, we cannot rule it out.

One potential concern with the present study is that the observed priming effect may actually reflect word sequence learning rather than structural priming. This concern arises because the prime and target sentences shared three words (e.g., trigram "selected by the"), and it is possible that this trigram repetition might have contributed to the priming effect. Though we did not test it directly, previous studies showed that "full relatives" (e.g., *The defendant who was examined by the lawyer was convicted ...*) and "short relatives" (e.g., *The defendant who was examined was convicted ...*) are as effective as reduced relatives (e.g., *The defendant examined by the lawyer was convicted …*) in priming reduced relative target sentences (Traxler, 2008; Traxler & Tooley, 2008). These results suggest that facilitated processing of the disambiguating *by*-phrase region of reduced relatives was due to the abstract relative clause structure, rather than the word sequence overlap between the prime and target sentences. However, given the fact that people can store multi-word sequences and make

generalizations over these stored exemplars (e.g., Bannard & Matthews, 2008; Chang, Janciauskas, & Fitz, 2012), it is difficult to completely rule out any contribution from trigram repetition.

Given that this is the first demonstration of persistent structural priming during online L2 comprehension, there are a number of issues that need to be addressed in future research. For instance, it remains to be tested whether the persistent priming effect can be extended to classroom settings, and whether the effect could be strengthened if supplemented with explicit instruction, as indicated in L2 production priming studies (e.g., Shin & Christianson, 2012). Experiments using substantially longer lags, of days or weeks after the initial priming event, are necessary to determine the durability of structural priming effects on L2 speakers. Future studies involving other syntactic structures, with and without verb repetition, are also needed.

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Table 1.

Sample sentences used in Experiment 1

Lag 0 condition	(Prime) The speaker selected by the group would be perfect for the program.
	(Target) The architect selected by the manager was educated at Yale.
Lag 1 condition	(Prime) The speaker selected by the group would be perfect for the program.
	(Filler 1) The baby was sleeping soundly in his mother's arms.
	(Target) The architect selected by the manager was educated at Yale.
Lag 2 condition	(Prime) The speaker selected by the group would be perfect for the program.
	(Filler 1) The baby was sleeping soundly in his mother's arms.
	(Filler 2) There are all kinds of birds and wild animals in the zoo.
	(Target) The architect selected by the manager was educated at Yale.

Table 2.

LME results for Experiment 1

	β	SE	t	df	p
Verb					
Intercept	565.3	29.3	19.28	51.6	< .001
Type	30.3	7.5	4.05	33.3	< .001
Lag	0.9	5.3	0.17	2235.1	.863
Type:Lag	5.5	5.3	1.02	2237.6	.306
Disambiguating By-phrase					
Intercept	1367.4	40.7	33.58	52.1	< .001
Type	33.8	8.3	4.07	32.0	< .001
Lag	10.4	6.8	1.52	2308.8	.128
Type:Lag	-3.1	6.8	-0.45	2310.7	.650
Post-disambiguation					
Intercept	911.7	27.0	33.78	59.5	< .001
Type	9.4	5.1	1.82	347.7	.069
Lag	5.2	5.3	0.99	117.8	.326
Type:Lag	2.8	4.9	0.57	2322.1	.568

Table 3.

LME results for Experiment 2

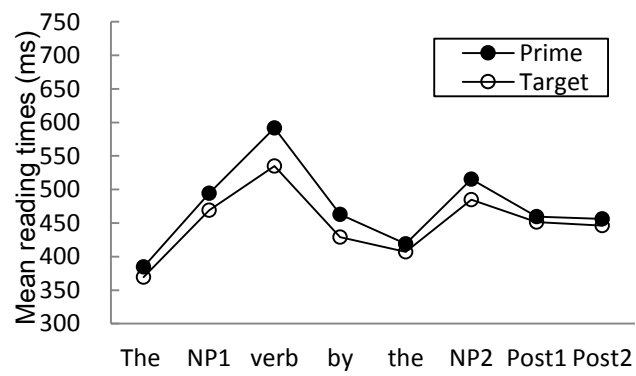|	β	SE	t	df	p
Verb					
Intercept	511.1	31.4	16.28	75.0	< .001
Type	12.3	8.2	1.51	47.3	.137
Lag	0.5	7.4	0.07	64.2	.946
Type:Lag	7.6	7.5	1.02	60.1	.314
Disambiguating By-phrase					
Intercept	1242.7	52.6	23.63	62.3	< .001
Type	19.2	8.9	2.16	108.1	.033
Lag	-0.6	7.8	-0.07	1548.3	.942
Type:Lag	-4.7	7.8	-0.60	1548.8	.547
Post-disambiguation					
Intercept	822.6	31.2	26.39	61.3	< .001
Type	5.3	5.7	0.94	1556.6	.349
Lag	-7.3	5.7	-1.29	1556.0	.199
Type:Lag	-2.7	5.7	-0.48	1556.6	.633

Figure Captions

Figure 1. Mean reading times under each lag condition at each word position for Experiment 1. Post-1 and Post-2 refer to the first two words following the disambiguating *by*-phrase.

Figure 2. Mean reading times from the target sentence under each lag condition at each word position for Experiment 2. MC-RC = main clause prime, reduced relative clause target; RC-RC = reduced relative clause prime, reduced relative clause target.

(a) Experiment 1, Lag 0

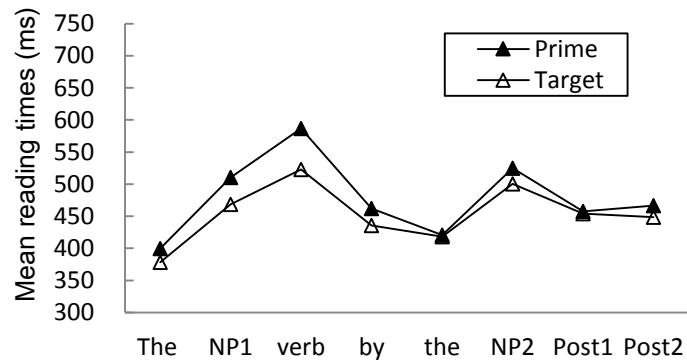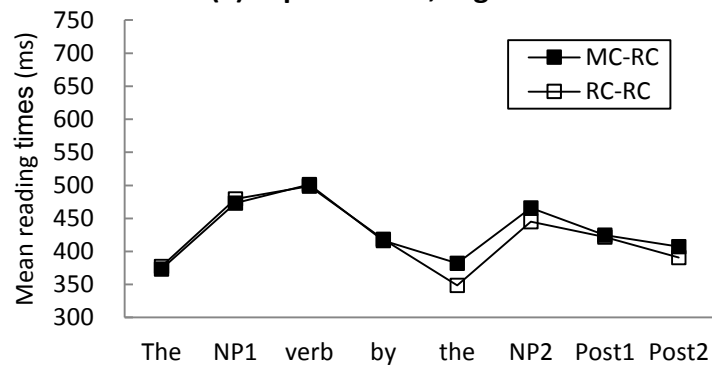**(b) Experiment 1, Lag 1**

(c) Experiment 1, Lag 2

Figure 1

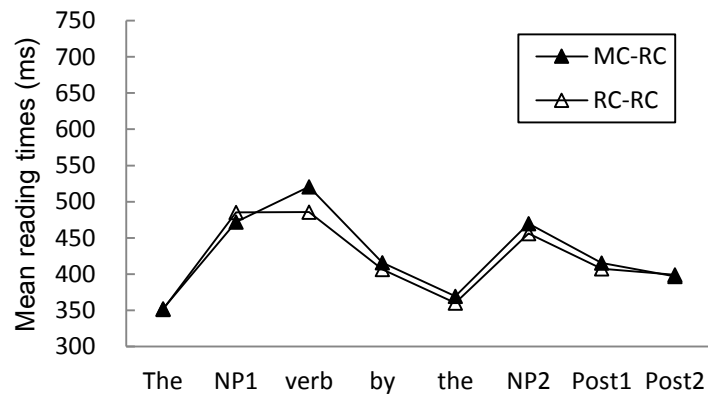**(a) Experiment 2, Lag 0**

(b) Experiment 2, Lag 2

Figure 2

Appendix

Stimuli for Experiments 1 and 2. The sentence before the first slash is the reduced relative prime used both in Experiment 1 and Experiment 2, and the sentence between the slashes is the main clause prime used only in Experiment 2. The sentence after the second slash served as the target in Experiments 1 and 2.

1. The speaker selected by the group would be perfect for the program. /The group selected the speaker who would be perfect for the program. /The architect selected by the manager was educated at Yale.

2. The director watched by the cop was in poor health. /The cop watched the director who was in a bad part of the town. /The mouse watched by the cat was hiding under a table.

3. The mailman expected by the secretary arrived with an important letter. /The secretary expected the mailman who arrived with an important letter. /The painter expected by the woman was right on time.

4. The spy transported by the police felt deeply worried. /The police transported the spy who felt deeply worried. /The prisoner transported by the guards was closely watched.

5. The singer loved by the fan had a very sweet voice. /The fans loved the singer who had a very sweet voice. /The teacher loved by the class was easy to understand.

6. The army attacked by the rebels moved forward slowly. /The rebels attacked the army that moved forward slowly. /The troops attacked by the enemy suffered heavy losses.

7. The teacher appreciated by the principal worked extremely hard. /The principal appreciated the teacher who worked extremely hard. /The secretary appreciated by the leader was very clever.

8. The cowboys surrounded by the Indians prepared to fight. /The Indians surrounded the cowboys who prepared to fight. /The lions surrounded by the hunters paced nervously.

9. The driver stopped by the policeman had been drinking. /The policeman stopped the driver who had been drinking. /The child stopped by the guard looked very upset.

10. The bird found by the biologist had beautiful features. /The biologist found the bird that had beautiful features. /The dog found by the hunter had a broken leg.

11. The man scolded by the police was extremely embarrassed. /The police scolded the man who was extremely embarrassed. /The child scolded by the mother went up the stairs.

12. The child injured by the dog cried for help. / The dog injured the child who cried for help. /The driver injured by the truck had to go to the hospital.

13. The spy caught by the FBI agent was from the Middle East. / The FBI caught the spy who was from the Middle East. /The criminal caught by the police was put in prison.

14. The actress recognized by the tourists was wearing sunglasses. / The tourists recognized the actress who was wearing sunglasses. / The criminal recognized by the victim was held for questioning.

15. The motorist helped by the firemen was trapped in the car. /The firemen helped the motorist who was trapped in the car. /The doctors helped by the nurses were awfully tired.

16. The zebra killed by the crocodile was crossing the river. /The crocodile killed the zebra that was crossing the river. /The deer killed by the train caused a large accident.

17. The dentist hated by his patients had a bad temper. / The patients hated the dentist who had a bad temper. /The boss hated by the workers was terribly rude.

18. The employee accused by the employer was not allowed to work. /The employer accused the employee who was not allowed to work. /The robber accused by the judge was punished severely.

19. The candidates considered by the board had won many awards. /The board considered the candidates who had won many awards. / The scientists considered by the committee each had limitations.

20. The man lifted by the elephant was quite nervous. / The elephant lifted the man who was quite nervous. /The monkey lifted by the trainer was hoping for a banana.

21. The clown pulled by the magician fell to the ground. /The magician pulled the clown who fell to the ground. /The girl pulled by her father wanted to stay at the zoo longer.

22. The pupil praised by the teacher studied extra longer that week. / The teacher praised the pupil who studied extra longer that week. /The player praised by the team leader soon obtained a scholarship.

23. The girl kissed by the singer got so excited that she fainted. / The singer kissed the girl who got so excited that she fainted. /The mother kissed by the boy gave him a hug in return.

24. The doctor cured by the specialist went back to work. / The specialist cured the doctor who went back to work. / The soldier cured by the medicine had been badly injured.

25. The principal fired by the school had been missing work. / The school fired the professor who had been missing work. /The accountant fired by the firm was arrested for drug possession.

26. The landlord cheated by the couple was not paid any rent. /The couple cheated the landlord who was not paid any rent. / The customer cheated by the company refused to purchase their product.

27. The clerk preferred by the judge was always on time. /The judge preferred the clerk who was always on time. / The waitress preferred by the princess got a large tip.

28. The housewife taught by the chef made a wonderful cake. /The chef taught the housewife who made a wonderful cake. / The student taught by her mother passed all tests.

29. The singer missed by the conductor had a sore throat. / The conductor missed the singer who had a sore throat. / The child missed by the bus had to walk to school.

30. The cleaner hired by the hotel had to work seven days a week. /The hotel hired the cleaner who had to work seven days a week. /The manager hired by the owner had to work 7 nights per week.

31. The rabbit washed by the maid was covered in dust. /The maid washed the rabbit that was covered in dust. The girl washed by her mother was very cold.

32. The typist punished by the editor had made many typing errors. /The editor punished the typist who had made many typing errors. /The worker punished by the boss cleaned up the workshop.

33. The actor recommended by the director was an Oscar winner. /The director recommended the actor who was an Oscar winner. / The governess recommended by the host was highly experienced.

34. The coach hugged by the player had an amazing career. /The player hugged the coach who had an amazing career. /The girl hugged by the grandparent felt safe and warm.

35. The defendant examined by the psychologist was found to be mentally stable. / The psychologist examined the defendant who was found to be mentally stable. /The player examined by the referee was allowed to finish the game.

36. The dancer criticized by the audience had a poor performance. /The audience criticized the dancer who had a poor performance. /The cook criticized by the customers used too much salt.