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ORIGINAL ARTICLE

Long-term structural priming involves a memory-based mechanism

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Abstract

Speakers adapt their syntactic preferences based on syntactic experience. However, it is not clear what cognitive mechanism underlies such adaptation. While error-based mechanisms suggest that syntactic adaptation depends only on the relative frequency of syntactic structures, memory-based mechanisms suggest that both frequency and recency of syntactic structures matter in syntactic adaptation. To distinguish between these two mechanisms, I manipulated the order of passive and active primes in two syntactic priming experiments, presenting passive primes either before active primes (active-recent condition) or after them (passive-recent condition), while controlling for frequency. The results showed that the magnitude of priming was numerically greater in the passive-recent condition than in the active-recent condition in Experiment 1, and significantly greater in Experiment 2. These results provide novel evidence that syntactic adaptation involves a memory-based mechanism.

Keywords: Adaptation; error-based learning; implicit learning; memory-based mechanism; structural priming; syntactic priming

Introduction

Research on structural priming has demonstrated that speakers' choices of syntactic structures are influenced by their prior syntactic experience. For instance, speakers are more likely to use a passive structure, as in "*the thief was caught by the police*" immediately after hearing someone say "*the mouse was chased by the cat*" (e.g., Bock, 1986). This immediate form of structural priming is often attributed to the transient activation of a recently processed syntactic structure (i.e., a residual activation account) (e.g., Dell, 1986; Pickering & Branigan, 1998; Branigan et al., 1999). According to this view, recent exposure to a given structure temporarily increases its activation relative to its alternatives, thereby increasing the likelihood that the speaker will subsequently produce that structure. Because immediate structural priming is driven by short-term activation, its effects are typically brief and do not persist over extended periods.

Syntactic experience, however, can also lead to long-term, cumulative effects on structural choices, which is the primary focus of the current study. For example, speakers are more likely to use a syntactic structure if they have encountered it repeatedly over time, a phenomenon known as cumulative structural priming (e.g., Hwang & Shin, 2019; Jaeger & Snider, 2013; Kaschak, 2007; Kaschak et al., 2006, 2011; Kaschak & Borreggine, 2008). This effect reflects how prior experience increases the overall likelihood of producing a given structure. Importantly, although more frequent structures are used more often overall, they tend to elicit smaller priming effects (i.e., inverse frequency effect) (e.g., Bock & Griffin, 2000; Hartsuiker & Westenberg, 2000; Jaeger & Snider, 2013; Scheepers, 2003). That is, while common structures like actives are produced more frequently due to greater cumulative experience, less frequent structures like passives typically produce stronger priming effects when they do occur.

Long-term, cumulative structural priming effects are typically explained in terms of implicit learning. Implicit learning models can be grouped into two broad categories in terms of how they derive structural priming effects: error-based models (e.g., Chang et al., 2006; Jaeger & Snider, 2013) and memory-based models (e.g., Reitter et al., 2011). Error-based models suggest that structural priming arises from an implicit learning mechanism driven by prediction error. According to this account, speakers generate predictions about upcoming words (Chang et al., 2006) or syntactic structures (Jaeger & Snider, 2013). If there is a discrepancy between their prediction and the actual input (i.e., prediction error), speakers adjust their production preferences in a way to minimize future prediction error. Each additional experience of a syntactic structure yields further adjustments until the system can make accurate predictions of upcoming linguistic input. Thus, each experience of a syntactic structure immediately increases the likelihood of its subsequent use (i.e., immediate priming), and the effects of multiple experiences accumulate over time (i.e., cumulative priming). Less frequent structures are less expected and therefore yield greater prediction errors and adjustments to the system. This explains why they elicit stronger structural priming effects.

Memory-based models account for structural priming in terms of activation in memory. In the model proposed by Reitter et al. (2011), in particular, activation consists of two components: base-level activation and spreading activation. In this model, the likelihood that a certain syntactic structure will be produced is determined by its activation in memory, and structural priming emerges from changes in base-level activation and/or spreading activation. Each time a sentence is processed, it increases the base-level activation of the syntactic structure in long-term memory, while lexical and semantic information in the sentence briefly spreads activation to associated syntactic structures (spreading activation). Base-level activation exhibits a power-law decay over time such that the more recent a retrieval, the stronger its impact. According to a power-law function, the increased base-level activation never fully decays to zero. Thus, the base-level activation of a syntactic structure slowly increases over time as a function of its retrieval. This increase in the base-level activation over time constitutes the long-term cumulative structural priming effect. Given that frequent structures have higher base-level

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activation, the increase in the base-level activation is proportionally smaller for frequent structures than for less frequent structures. Thus, structural priming is weaker for more frequent structures.

Both error-based and memory-based models claim that speakers are sensitive to the relative frequencies of syntactic structures, such that the more they have experienced a particular syntactic structure, the more likely they are to use that structure (e.g., Hwang, 2022; Jaeger & Snider, 2013; Kaan & Chun, 2018; Kaschak & Borreggine, 2008; Kaschak et al., 2006; Shin & Christianson, 2012). They also suggest that speakers show stronger priming for less frequent structures (e.g., Bock & Griffin, 2000; Ferreira, 2003; Hartsuiker & Kolk, 1998; Hartsuiker et al., 1999; Hartsuiker & Westenberg, 2000; Hwang & Shin, 2019; Jaeger & Snider, 2013; Scheepers, 2003). Thus, they both predict long-term cumulative priming effects as well as inverse frequency effects.

The two models, however, make different predictions about whether speakers are sensitive to the temporal placement of syntactic structures—that is, how syntactic structures are distributed over time. In error-based models, the strength of priming is solely determined by the frequency with which speakers have encountered particular syntactic structures (e.g., Chang et al., 2006; Jaeger & Snider, 2013). As a result, the temporal distribution of these structures, whether exposure occurs recently or earlier, is considered irrelevant. These models suggest that priming effects should be comparable as long as the total amount of exposure is equivalent.

In memory-based models, however, the magnitude of priming depends not only on the frequency of syntactic structures but also on the temporal placement of the structures, due to a power law decay of the base-level activation. According to these models, given equivalent exposure to a particular structure, priming effects should be stronger when the structure has been encountered more recently.

Consistent with the prediction of error-based models, Kaschak et al. (2006) did not find any evidence that the temporal placement of prime sentences affected structural priming. In two experiments, each conducted in two phases, English speakers received a prime stem designed to elicit the production of a double object (DO) construction (e.g., *Jennifer gave her daughter* . . .) or a prepositional object (PO) construction (e.g., *Jennifer gave the doll* . . .). During the first phase, participants were exposed to only prime stems. Kaschak et al. manipulated the temporal distribution of DO and PO primes by alternating the two structures (e.g., PO-DO-PO-DO . . .) or presenting them in blocks (e.g., PO-PO- . . . - DO-DO . . .). During the second phase, participants received a target stem (e.g., *Diana gave* . . .) immediately after a PO or DO prime stem. Target stems provided participants with the opportunity to produce either a DO or a PO construction. In both experiments, Kaschak et al. found that the temporal manipulation of prime sentences in the first phase did not influence the production of target sentences in the second phase.

The results of Kaschak et al. (2006), however, do not provide strong evidence that the temporal distribution of syntactic structures did not affect structural priming. There are at least two possible explanations for why Kaschak et al. (2006) did not find any effect of the temporal distribution. One possibility is that following the temporal manipulation of primes in the first phase, participants were exposed to a DO or PO prime for each trial in the second phase. If the effect of the temporal manipulation was subtle, it is possible that the potential effect of temporal manipulation was overridden by an immediate priming effect. A second possibility, not mutually exclusive with the first, is that the temporal manipulation of primes was not strong enough. Kaschak et al. (2006) manipulated the temporal distribution of primes by alternating or blocking alternative syntactic structures. Since the alternative structures were evenly spaced in the alternating condition (e.g., PO-DO-PO-DO . . .), the syntactic structure that occurred recently in the block condition (e.g., DO in PO-PO- . . . - DO-DO . . .) also appeared in some of the recent trials in the alternating condition. Thus, participants' recent experience of a particular structure in both conditions may have made it difficult to detect the effect of the temporal manipulation if the effect was subtle.

Here, I revisit the question of whether the temporal distribution of structures matters in structural priming with experimental set-up and measures that are designed to better detect the effect of the temporal distribution. Following Hwang and Shin (2019), I employed a pretest-priming-posttest design. In all phases of the study, the participants' task was to describe transitive pictures. The pretest and posttest phases allowed participants to choose between the active and passive structures, whereas the priming phase required participants to produce primed structures.

Crucially, several measures were taken to maximize the likelihood of observing an effect of temporal distribution. In the priming phase, I manipulated the temporal distribution of primed structures, such that a set of active primes was followed by a set of passive primes (Passive-recent condition: Active-Active- . . . -Passive-Passive- . . .) or a set of passive primes was followed by a set of active primes (Active-recent condition: Passive-Passive- . . . -Active-Active- . . .). These two conditions maximize the contrast in the temporal distribution of active and passive primes, and thus make it easier to capture any effect of temporal distribution. Participants also did not receive any prime in the posttest phase. This eliminates the possibility of the effect of the temporal manipulation in the priming phase being overridden by immediate priming in the posttest.

I also tested priming effects in native (L1) and non-native language (L2) processing. Research on structural priming reveals notable similarities between L1 and L2 speakers despite some differences. Both groups exhibit immediate priming (e.g., Bock, 1986; Kaschak, 2007; Kim & McDonough, 2008; Schoonbaert et al., 2007), long-term cumulative priming (e.g., Jackson & Ruf, 2017; Jaeger & Snider, 2013; Kaan & Chun, 2018; Kutta et al., 2017), and inverse frequency effects (e.g., Bovolenta & Marsden, 2024; Jaeger & Snider, 2013; Kaan & Chun, 2018; Kaschak, 2007). These converging patterns suggest that L2 speakers are not inherently different from native speakers with respect to structural priming. In fact, it is suggested that structural priming in both L1 and L2 is supported by the same underlying mechanism, with differences between the groups explained by the same factors that drive individual variation within each group (Bovolenta & Marsden, 2022; Kaan, 2014).

One difference between L1 and L2 priming relevant to the present study is that L2 speakers may exhibit greater sensitivity to priming than native speakers, although the underlying reason for this difference remains unclear. In particular, Montero-Melis and Jaeger (2020) found that when primed to express the manner or path of motion, Swedish (L1) speakers of Spanish (L2) showed stronger priming

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effects than L1 Spanish speakers. Their primary aim was to investigate the extent to which L2 learners adapt their production based on L1 or L2 knowledge. The results revealed that less proficient L2 speakers were more influenced by their L1 (Swedish), whereas highly proficient speakers relied more on their L2 (Spanish). Importantly, irrespective of proficiency level, L2 Spanish speakers exhibited greater overall sensitivity to priming compared to L1 Spanish speakers.

Assuming that L1 and L2 structural priming are supported by the same underlying mechanism (Bovolenta & Marsden, 2022; Kaan, 2014), testing structural priming in L1 and L2 can provide more robust evidence as to whether the temporal distribution of syntactic structures matters or not in structural priming. On the one hand, if the temporal distribution of syntactic structures does not affect structural priming as suggested by error-based models, speakers would be insensitive to the temporal manipulation not only in L1 but also in L2, despite their greater sensitivity to L2 input. On the other hand, if the temporal distribution of syntactic structures does affect structural priming as suggested by memory-based models, speakers' greater sensitivity to L2 input could make any effects of the temporal manipulation more readily detectable. Thus, by testing priming in both L1 and L2, I aim to maximize the likelihood of observing temporal distribution effects.

To test whether structural priming is influenced by the temporal distribution of primes, I examined how Mandarin speakers' production of actives and passives was affected by the temporal manipulations in their native language (L1), namely, Mandarin (Experiment 1), and non-native language (L2), namely, English (Experiment 2). The predictions are the same for Experiments 1 and 2. Error-based and memory-based models predict that speakers would produce more passives in the posttest than in the pretest, both in the active-recent and passive-recent conditions (PRs). They encounter the same number of actives and passives in the two conditions, but due to stronger priming of the less frequent passive structure, participants would show a higher likelihood of using a passive structure in the posttest. Crucially, if error-based models are correct, the priming effects should not differ between the active-recent and PRs. If memory-based models are correct, however, the priming effect should be stronger in the PR than the active-recent condition (AR). That is, the increase in passive responses from pretest to posttest should be greater in the PR than in the AR due to the recent occurrences of passives.

Experiment 1: Mandarin

Method

Participants

The participants were 32 native Mandarin speakers from the University of Hong Kong. They received HK$100 in exchange for their participation.

Materials

The experiment used 48 transitive line drawing images and 72 filler images (Figure 1). These images were taken from Hwang and Shin (2019) and Slevc (2007). The transitive images depicted six transitive events (咬 "bite," 抓住 "catch," 跟踪 "follow," 打 "hit," 踢 "kick," 推 "push") involving an agent and a patient. Pictures were counterbalanced for position of agent/patient.

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Figure 1. Example of transitive event used in Experiment 1.

The pretest and posttest consisted of 12 images, with each verb used in two images. The priming phase consisted of 24 images, with each verb used in four images. Each image in the priming phase was paired with a sentence fragment designed to induce the production of an active sentence (e.g., "____打了____。" "____ hit ____.") or a passive sentence (e.g., "____被____打了。" "____ was hit by ____."). There were two conditions in Experiment 1. In the PR, 12 active primes were followed by 12 passive primes. In the AR, 12 passive primes were followed by 12 active primes. Participants were randomly assigned to one of the two conditions.

The target images were combined with 18 filler images in the pretest and posttest, and 36 filler images in the priming phase. The filler images were similar to the targets in style, but they depicted intransitive or dative events. To make the event being depicted clear, all pictures were accompanied by a verb and nouns to be included in the description. The order of trials was pseudo-randomized with constraints that no more than two target images occurred consecutively, and consecutive images did not share a character or a verb.

Procedure

Participants first performed a pretest and entered a priming phase, followed by a posttest. In the pretest and posttest, participants were instructed to describe pictures in one sentence using the words presented in the pictures. In the priming session, participants were told to describe the pictures by completing the sentence fragments using the words provided in the pictures. At the end of each trial, participants pressed a space bar to proceed to the next trial. The experiment was run on Paradigm software, and the participants' speech was recorded with a desk microphone.

Coding

Participants' responses in the pretest and posttest were transcribed and analyzed for their choices of active or passive structures. A target description was scored as "active" if it was a complete sentence that contained an agent as a subject, a verb, and

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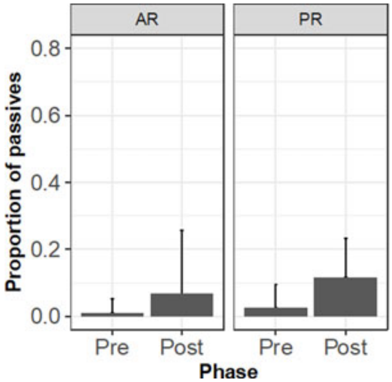

Figure 2. Proportions of passive responses in the active-recent condition (AR) and passive-recent condition (PR) in Experiment 1. Error bars indicate standard errors.

a patient as an object. A target description was scored as "passive" if it contained a patient as a subject, a bèi (被)-phrase including an agent as an object, and a verb. Descriptions were scored as "other" if they did not contain an agent, a patient, or a verb (e.g., 海盗打了 "the sailor hit"); if participants altered their referential or structural choice (e.g., 水手…海盗打了水手 "the sailor… the pirate hit the sailor"); if participants used a different word than provided (e.g., 强盗 "burglar" instead of 海盗 "pirate"); or if participants used a structure other than a canonical transitive structure (e.g. 海盗把水手打了 "the sailor, the burglar hit"). About 4.6% of the responses (35 out of 768) fell into the "other" category. "Other" responses were excluded from the analysis below.

Responses in the priming phase were scored as "correct" if participants eventually produced an appropriate description of the event, despite an initial change in reference or structure. Otherwise, the same criteria in the pretest and posttest were used for "other" responses. "Other" responses made up about 1.3% of the data (10 out of 768).

Analysis

I analyzed participants' responses using mixed-effects logistic regression using the *lme4* package in R 4.2.2 (R Development Core Team, 2022). The dependent variable was response form (Active = 0, Passive = 1). Fixed effects included were phase (sum-coded: Pretest = −0.5, Posttest = 0.5), temporal distribution (sum-coded: Active-recent = −0.5, Passive-recent = 0.5), and the interaction between the two. Models were fitted with the maximal random effects structure (Barr et al., 2013). If the fully maximal model did not converge, I simplified random slope structure until convergence was achieved. The most maximal model included by-participant and by-item random intercepts.

Results and discussion

Figure 2 plots the proportions of passive responses in the AR and the PR.

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Table 1. Summary of the mixed-effects logistic regression models for the likelihood of producing a passive in Experiment 1

Fixed Effects	Estimate	SE	*z*	*p*
Intercept	−4.48	0.63	−7.15	<.001
Phase	2.03	0.54	3.72	<.001
Temporal distribution	1.82	0.97	1.88	.060
Phase x Temporal distribution	−0.59	1.00	−0.59	0.55

As predicted by both error-based and memory-based models, participants produced more passives in the posttest (9.3%) compared to the pretest (1.9%). The logistic regression analysis (Table 1) showed that the effect of phase was significant.

The critical question was whether participants would show a higher likelihood of priming in the PR than in the AR. The PR led to a higher increase in passive production (8.9%) than the AR (5.7%), in line with memory-based models. The difference, however, did not reach significance, i.e., the interaction between phase and temporal distribution was not significant.

In sum, although I did not find conclusive evidence in favor of memory-based models, the numerical patterns of results point to memory-based mechanisms, in which structural priming is modulated by the temporal distribution of structures.

In Experiment 1, the effect of the temporal distribution may not have been clearly seen because the effect was relatively weak. Given that speakers are more susceptible to L2 input (Montero-Melis & Jaeger, 2020), a stronger effect of the temporal distribution could emerge in L2 priming. To better detect the effect of the temporal distribution, Experiment 2 tests the effect of the temporal distribution on Mandarin speakers' production of actives and passives in English. If the memory-based implicit learning mechanism indeed underlies structural priming, I predict that Mandarin speakers would show a greater likelihood of priming in the PR than in the AR.

Experiment 2: English

Method

Participants

Thirty-five Mandarin speakers of English from the University of Hong Kong participated in the experiment in exchange for HK$100. None of these participants participated in Experiment 1. They were asked to complete an English proficiency test adapted from Michigan English Language Institute College English Test (MELICET, www.michigan-proficiency-exams.com/melicet.html), followed by a language background questionnaire. Most participants were intermediate speakers of English (mean International English Language Testing System (IELTS) score: 7.03) with limited time spent in an English-speaking environment. The mean score of MELICET was 33 out of 50 (range 18–46).

Materials and procedure

The materials and procedures were identical to those in Experiment 1, except that the pictures appeared with English verbs and nouns (e.g., *hit*, *pirate*, *sailor*). In the

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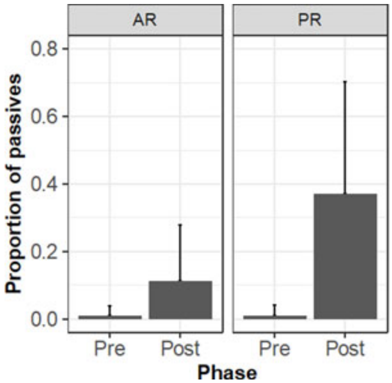

Figure 3. Proportions of passive responses in the active-recent condition (AR) and passive-recent condition (PR) in Experiment 2. Error bars indicate standard errors.

priming phase, each picture was also presented with an English sentence fragment (e.g., ____ *was hit by* ____.).

Coding

Criteria for coding were identical to those used in Experiment 1, except that for the "passive" category, a target description contained a patient as a subject, a be verb followed by a participle, and a by-phrase including an agent as an object.

Responses in the "other" category were excluded from further analysis. "Other" responses occurred in about 3.3% of the trials in the pretest and posttest (28 out of 840) and 1.7% of the trials in the priming phase (15 out of 840). As I was most interested in the syntactic structure of the participant's response, utterances that did not contain articles (e.g., *pirate hit sailor*) or use a correct verb form (e.g., *hitted*) were not excluded.

Analysis

Using logistic mixed effects regression, I analyzed participants' responses (Active = 0, Passive = 1) as a function of phase (sum-coded: Pretest = −0.5, Posttest = 0.5), temporal distribution (sum-coded: Active-recent = −0.5, Passive-recent = 0.5), and the interaction between the two. Models were fitted with the maximal random effects structure and simplified until convergence. The most maximal model included by-participant and by-item random intercepts.

Results and discussion

Figure 3 shows the proportions of passive responses in the AR and the PR.

There was a significant effect of phase, such that participants produced more passives in the posttest (23.8%) than in the pretest (1.0%) (Table 2). The increase in passive production from pretest to posttest was larger in Experiment 2 (22.8%) than in Experiment 1 (7.4%) (see Table 3 for a combined analysis of Experiments 1 and 2). This suggests that the priming effect was more pronounced in L2 than in L1, consistent with the findings of Montero-Melis and Jaeger (2020).

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Table 2. Summary of the mixed-effects logistic regression models for the likelihood of producing a passive in Experiment 2

Fixed Effects	Estimate	SE	*z*	*p*
Intercept	−4.37	0.60	−7.32	<.001
Phase	4.23	0.73	5.76	<.001
Temporal manipulation	1.24	0.95	1.31	.19
Phase x Temporal manipulation	2.45	1.35	2.16	.03

Table 3. Summary of the linear regression model for the magnitude of priming from the combined dataset

Fixed Effects	Estimate	SE	*t*	*p*
Intercept	0.15	0.03	5.80	<.001
Language	0.16	0.05	3.08	.003
Temporal distribution	0.15	0.05	2.90	.005
Language x Temporal distribution	0.23	0.11	2.14	.003

Crucially, the logistic regression analysis revealed a significant interaction between phase and temporal distribution, suggesting that the priming effect was larger in the PR (36.1%) than in the AR (10.3%). Planned comparisons showed that the priming effects were significant in both AR ($\beta = 2.87$, SE $= 0.82$ $z = 3.49$, $p <$ .001) and PR ($\beta = 5.86$, SE $= 1.11$ $z = 5.29$, $p < .001$). These results provide strong support for memory-based models that suggest that more recent syntactic experience yields a stronger priming effect.

Compared to Experiment 1, Experiment 2 obtained a greater overall priming effect and a more robust effect of the temporal distribution. To directly compare the results of Experiments 1 and 2, I conducted an analysis on the combined data from the two experiments. I tested if priming effects were modulated by language and temporal distribution, as well as an interaction between the two. Priming effects were calculated for each participant by subtracting the proportion of passives produced in the pretest from the proportion produced in the posttest. Higher scores indicate stronger priming effects. I fitted a linear regression model with the score as the dependent variable and language (sum-coded: Mandarin $= -0.5$, English $= 0.5$), temporal distribution (sum-coded: Active-recent $= -0.5$, Passive-recent $= 0.5$) and the interaction between the two as fixed effects.

The results of the combined analysis revealed main effects of language and temporal distribution (Table 3). Priming effects were stronger in English than in Mandarin, and in the PR than in the AR. The main effect of temporal distribution supports memory-based models. The interaction between language and temporal distribution was significant. Planned comparisons revealed that priming effects were significantly modulated by the temporal distribution in English ($\beta = 0.27$, SE $= 0.09$, $t = 3.07$, $p = .004$), but were unaffected by the temporal distribution in Mandarin ($\beta = 0.04$, SE $= 0.06$, $t = 0.72$, $p = .48$). These results suggest that

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participants demonstrated greater sensitivity to priming, with the magnitude of the priming effect being larger in English.

General discussion

Using a pretest-priming-posttest design, Experiments 1 and 2 tested whether Mandarin speakers' production of actives and passives was affected by the temporal distribution of primes (AR vs. PR) in Mandarin and English, respectively.

In both Mandarin and English, error-based and memory-based models predict that Mandarin speakers would produce more passives in the posttest compared to the pretest in both the active-recent and PRs. The two models, however, make different predictions regarding the temporal distribution of primes. Whereas error-based models predict that Mandarin speakers' production of actives and passives would not differ between the active-recent and PRs, memory-based models predict that Mandarin speakers would produce more passives in the PR.

As predicted by both models, Mandarin speakers produced more passives in the posttest compared to the pretest in both Mandarin and English, regardless of the temporal placement of primes. Consistent with Montero-Melis and Jaeger (2020), the priming effect was larger in English than in Mandarin. To the best of my knowledge, this is the first study to replicate and extend Montero-Melis and Jaeger's findings.

Crucially, I found evidence that structural priming was modulated by the temporal distribution of primes. Temporal distribution had a significant effect on passive production in the combined dataset. In a separate analysis, the priming effect was greater in the PR than in the AR in English. These findings are consistent with memory-based models that posit stronger effects for more recent primes.

In Mandarin, however, the priming effect was not significantly different between the two conditions, although participants produced numerically more passives in the PR. This raises an important question: if the same memory-based implicit learning mechanism underlies the production of actives and passives in both Mandarin and English, why did Mandarin speakers show a weaker sensitivity to the temporal manipulation in Mandarin?

Under memory-based models, the difference between Mandarin and English can be explained in terms of the difference in the base-level activation. Mandarin transitive structures are much more frequent than English transitive structures in Mandarin speakers' input. Thus, they have higher base-level activation than English transitive structures. The difference between Mandarin and English then follows because the activation boost associated with processing a recent transitive prime will be proportionally much smaller for Mandarin transitive structures than English transitive structures. In general, transitive primes yield a smaller relative increase in the activation of transitive structures in Mandarin due to their higher base-level activation. Since the activation boost constitutes the priming effect, the smaller activation boost in Mandarin accounts for weaker effects of priming and temporal distribution in Mandarin.

Note that a weaker overall priming effect in Mandarin can also be explained within error-based models. Mandarin speakers are likely to experience a lower prediction error when processing Mandarin transitive sentences, to which they have had lifelong exposure, compared to English transitive sentences with limited

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exposure. The lower prediction error in Mandarin causes a smaller adjustment to the syntactic system and hence a weaker priming effect in Mandarin. Error-based models, however, suggest that the priming effect is determined only by the relative frequency of syntactic alternatives, and thus cannot account for the effect of the temporal manipulation.

The larger priming effect in L2 compared to L1, whether due to differences in base-level activation (memory-based models) or to prediction error (error-based models), has important implications for the nature of L1 and L2 representations in bilinguals. Hwang and Shin (2019) demonstrated that intermediate Mandarin-English bilinguals, a population similar to that of the current study, exhibit cross-linguistic structural priming for transitives (actives/passives) across the two languages, suggesting that representations for these structures are shared between L1 and L2. However, if these representations are equally activated in L1 and L2, one would not expect priming effects to differ across the two languages. The differing sensitivity to primes observed in the present study suggests that the shared representations may be differently activated during L1 and L2 production, possibly shaped by bilinguals' relative experience in each language. If so, between-language priming (L1-to-L2 or L2-to-L1) would be expected to be weaker than within-language L2 priming. For example, in English-to-Mandarin priming, Mandarin-English bilinguals may exhibit increased sensitivity to English primes. However, this effect may be attenuated by their greater experience with Mandarin, resulting in reduced adaptation compared to English-to-English priming. In contrast, in Mandarin-to-English priming, the priming effect in Mandarin may be amplified, leading to greater adaptation in English compared to Mandarin-to-Mandarin priming. Future research should investigate the sources of these differences and clarify the nature of bilingual structural representations.

Although the effect of the temporal manipulation and its stronger effect in English are well accounted for by memory-based models, there is an alternative account of the stronger effect of temporal distribution in English. That is, the effect is related to participants' production difficulty in English. Due to limited exposure to English transitive structures, Mandarin speakers are likely to be less confident and experience more difficulty in their production of English transitive structures. Thus, to reduce production difficulty, Mandarin speakers tend to repeat recently experienced structures in English to a greater extent than they do in Mandarin. This explanation, however, fails to account for priming of passives in the AR in English. If Mandarin speakers simply repeat recently experienced structures in English, they should produce more actives in the posttest than in the pretest in the AR. Since actives are easier to produce and have been recently experienced, Mandarin speakers have no reason to produce more passives in the posttest. Yet contrary to the prediction, Mandarin speakers did produce more passives in the posttest compared to the pretest in the AR in English. Although production difficulty may have played a role, it alone cannot account for the patterns of priming in Mandarin and English.

If the difference in the base-level activation is the correct explanation for the difference between Mandarin and English, I expect that children would show a stronger effect of the temporal manipulation than adults. Compared to adults, children have less experience with transitive structures, and thus the base-level activation of transitive structures would be lower in children. If children receive a relatively greater boost from recently experienced transitive structures, this should yield stronger effects of priming and temporal distribution in children than in adults. There is evidence that children show stronger immediate and cumulative priming than adults (Branigan & Messenger, 2016; Rowland et al., 2012), but it is not yet known how the temporal distribution of structures affects children's sentence production compared to adults. Future work is necessary to determine the effect of the temporal distribution in children and adults.

In conclusion, this paper provides novel evidence that the temporal distribution of syntactic structures affects structural priming in support of memory-based implicit learning models. By demonstrating the effect of the temporal distribution of primes in structural priming, the results of the study help refine our understanding of the nature of the implicit learning mechanism underlying structural priming.

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Replication package. Replication data and materials for this article can be found at https://osf.io/pgb8e/.

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