Error-based Structure Prediction in Comprehension: Evidence from verb bias effects in a visual-world structural priming paradigm for Mandarin Chinese

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Abstract

Structural priming studies in production have demonstrated stronger priming effects for unexpected sentence structures (inverse preference effect). This is consistent with error-based implicit learning accounts that assume learning depends on prediction error. Such prediction error can be verb-specific, leading to strong priming when a verb that is for instance biased towards the prepositional object(PO) structure occurs with an unexpected double object(DO) structure. However, it is unclear whether this mechanism also holds for language comprehension, especially for languages like Mandarin Chinese, which arguably depends strongly on semantics to predict syntax in comprehension. Experiment 1 was a norming study (N=367) that measured the biases (DO vs. PO) of 48 Mandarin Chinese dative verbs. Experiment 2 (N=72) crossed verb bias (DO-bias or PO-bias) and structure (DO or PO) of prime sentences in a visual-world paradigm, to examine whether Mandarin comprehenders show an inverse preference effect. The priming effect is expressed as the proportion of looks to the predicted referent (i.e., the recipient after a DO-prime, the theme after a PO-prime), for two critical time windows during target sentence processing: the verb and the first syllable of the first post-verbal noun (which was identical in theme and recipient). There was priming in both time windows, even though the verb differed between prime and target. Importantly, there was an inverse preference effect (i.e., stronger priming after a DO prime with a PO-biased verb than with a DO-biased verb) in the second time window. These results provide evidence for an error-based structure prediction system in comprehension.

Key words: Implicit learning; verb bias; structural priming; comprehension; Mandarin Chinese

Introduction

In order to efficiently process a sentence during language comprehension, people make predictions from previous experience (e.g., “it was a windy day so the boy went to the park to fly a kite”) to overcome the noise of variable input (Levy, 2008). They will predict many aspects of the upcoming words, including semantic (e.g., “kite” is inanimate) and syntactic (e.g., word category, “kite” is a noun) information. Moreover, they will also predict larger units of syntax, such as the structure of a verb phrase (e.g., dative structure, double object (DO) “show the horse the book” or prepositional object (PO) “show the horn to the dog”) (DeLong et al., 2014; Thothathiri & Snedeker, 2008a). But it is still unclear what mechanism generates these predictions of structure in language processing. In this study, we investigated the predictions of an implicit learning account, which assumes an error-based prediction system. Specifically, because comprehenders aim to minimize prediction error during language processing, they rapidly adapt upon experiencing prediction error and thereby continuously renew the syntactic system that generated the structure prediction (Chang, 2000; Chang et al., 2006). We will test this model’s prediction that encountering a verb together with an unexpected structure (hence large prediction error) results in relatively large structural priming in comprehension.

Structural priming is the tendency for speakers and comprehenders to re-produce or predict the syntactic structures of a recently processed prime sentence in the target sentence (Bock, 1986b, 1986a; Mahowald et al., 2016; Pickering & Branigan, 1998). For example, speakers tend to produce DO sentences more often after processing DO sentences than after PO sentences (Bock, 1986b). Importantly, structural priming is influenced by the structural preference of individual verbs (so-called verb bias). Jaeger and Snider (2013) calculated the bias for the alternative structure of each prime verb (Jaeger & Snider, 2008), based on a corpus of speech production (Bresnan et al., 2007). For example, speakers prefer to follow the English verb “show” with the DO structure rather than the PO structure. Because of the existing bias towards DO, the verb “show” followed by a PO structure in the prime leads to a substantial prediction error. The degree of prediction error depends on the extent to which a given verb biases towards the specific structure. Jaeger and Snider found that when the prime verb was followed by a more surprising structure (hence larger prediction error), speakers were more likely to reuse the structure from the primes, in both spoken and written production of target sentences, indicating a cross-modality inverse preference priming effect. Similar results were found in Dutch, when verb bias was calculated from a picture

description task with specific verbs (Bernolet & Hartsuiker, 2010). Additionally, the inverse preference priming effect was found in two age groups of children (3-4 or 5-6 years old) and adults (Peter et al., 2015). This inverse preference priming effect supports an important assumption of implicit learning accounts, namely that the acquisition of syntax is based on the prediction error for the upcoming word (Chang et al., 2006). This account claims that when the prediction does not match the actual input, like PO after “show”, the increased error will strengthen the connection weights of the units that represent the experienced structure. These weight changes then lead to increased use of this experienced structure. Therefore, this account claims that structural priming is a form of implicit learning, and that it is driven by prediction errors after recent exposure as the system aims to decrease future prediction errors (Bock & Griffin, 2000; Chang, 2000; Chang et al., 2006).

The inverse preference effect in language production thus supports an error-based prediction account (Chang et al., 2006). According to this account, the same error-based prediction mechanism is responsible for structural priming in comprehension as well. However, in contrast to the robust finding of stable structural priming when the verb differs between prime and target in production, only some comprehension studies showed such abstract structural priming (Thothathiri & Snedeker, 2008a, 2008b; Traxler, 2008), whereas other studies did not (Arai et al., 2007; Branigan et al., 2005; Ziegler & Snedeker, 2019). For instance, Arai et al. (2007) observed structural priming when the verb was repeated between prime and target in a visual world paradigm. Specifically, participants looked more often at the animate recipient (predicting DO structure) than at the inanimate theme after the processing of DO primes, when they heard the target verbs; they looked more at the theme (predicting PO structure) than recipient after PO primes. However, such priming disappeared when the verb differed from prime and target, suggesting a lexically dependent priming effect in comprehension. In contrast, Thothathiri and Snedeker (2008a) reported evidence for lexically independent priming. These authors used an act-out task that made the post-verbal arguments after the target verb more unpredictable than in Arai et al.’s study. Moreover, there was initial phonemic overlap between recipients and themes in target sentences (e.g., “horse” vs. “horn”) and there were two primes with the same structure, embedded in a story context, before the target sentences. There was structural priming in the time window of the first noun phrase (e.g., “hor...”) for both three- and four-year-old children and adults even though the verbs were different (Thothathiri & Snedeker, 2008a, 2008b). The presence of such lexically

independent priming, similar to the findings in production, supports the hypothesis of a shared syntactic processing mechanism in production and comprehension (Traxler, 2008).

Is this lexically independent structural priming in comprehension induced by an error-based prediction mechanism? One way of testing this is to assess the inverse preference priming effect in comprehension, similar to the studies in production. Fine and Jaeger (2013) addressed this issue by re-analyzing the eye-tracking data of Thothathiri and Snedeker (2008a) to investigate whether priming in comprehension depended on prediction errors in primes. To estimate prediction error, they performed a sentence-completion task and then calculated the alternation structure bias (the probability of DO vs. PO responses) for each of Thothathiri and Snedeker's prime sentences. There was an interaction between the structure bias of the first prime sentences (not for the second prime sentences) and prime structure (DO vs. PO) such that priming was stronger when prime structure was more surprising. The findings are consistent with the results of production studies (Jaeger & Snider, 2013). However, Fine and Jaeger's study was not an experimental study but a re-analysis of an existing experiment that did not originally control structure bias and that was not set up to address the question of error-based prediction.

Below, we report a controlled experiment that tests whether there is an error-based structure prediction mechanism in comprehension, which is responsible for both lexically independent structural priming and inverse preference priming. Such a test is important, because: 1) previous evidence for lexically independent structural priming in comprehension is mixed; 2) it is not clear whether such evidence is based on the specifics of the task (e.g., having two primes rather than one); 3) there is no experimental evidence for an inverse preference effect in comprehension (only a reanalysis of an experiment not designed to address that question); 4) the existing evidence is restricted to only a single language (English).

Our study therefore adds to the existing literature in at least two important ways. First, we manipulated verb bias and prime structure experimentally in a visual world paradigm. In contrast, the experiment that Fine and Jaeger (2013) reanalyzed did not strictly manipulate verb bias and used two prime sentences before each target sentence. The repeated exposure of unexpected structure might have led to adaptation and so decreased the effect of prediction error, which might be the reason that there was no inverse preference priming with the second prime sentences. Therefore, we only presented one prime sentence before the target sentences. If structure prediction

depends on the error-based mechanism, we expect an interaction between structural priming and verb bias.

Second, we investigated structure prediction in the comprehension of Mandarin Chinese, a language with flexible word order and few explicit markers of syntactic structure. In particular, Mandarin lacks morphophonological markers like case, tense, grammatical gender, and number, which many languages use as direct cues to distinguish the grammatical roles of the sentence constituents. This results in a difficulty to detect syntactic information (i.e., category) of individual words. A further source of potential difficulty is that Mandarin allows various word orders (i.e., SVO, OSV, SOV, VOS) (P. Li, 1996; P. Li et al., 1993; L. Zhang, 1997). These properties might result in a difficulty to predict or pre-access structure information independently before access of the target verb in the bottom-up processing of comprehension. Indeed, many Mandarin comprehension studies proposed that semantic processing precedes syntactic processing (Wang et al., 2013; Yang et al., 2009; Y. Zhang et al., 2013). However, structure prediction may involve abstract structural knowledge rather than lexically dependent knowledge (Perek & Goldberg, 2015, 2017; Thothathiri & Braiuca, 2020; Thothathiri & Rattinger, 2016). If an error-based prediction mechanism involving abstract structure representation holds for all languages, we expect structural priming in Mandarin, similarly to English.

In the eye-tracking experiment reported below we needed to strictly control the level of verb bias in prime and target. Therefore, we normed a large number of Mandarin dative verbs in Experiment 1 for verb bias. Earlier studies on structural priming in Mandarin showed a preference for the PO structure over the DO structure in production (Z. Cai et al., 2011, 2012, 2015; Chen et al., 2019; Huang et al., 2016, 2019). We therefore expected to find a PO-bias overall, but possibly with considerable variation among dative verbs. Then in Experiment 2, we investigated inverse preference priming within a visual world paradigm (Arai et al., 2007). In the paradigm, participants first read aloud written prime sentences and then listened to spoken target sentences while looking at pictures with corresponding objects, allowing us to detect syntax-based predictions in real time (Huettig et al., 2011; Tanenhaus et al., 1995). We manipulated the verb bias (DO-bias vs. PO-bias) and structure type (DO vs. PO) in the prime sentences. The target verbs differed from prime verbs and had no obvious preference for DO or PO. If comprehension involves a lexically independent representation of syntax in Mandarin, structural priming should occur even when the verb is not repeated between the prime and target. Importantly, if comprehension involves error-based

prediction, structural priming should interact with the structural bias of the specific verb, so that priming is stronger when verb bias mismatches prime structure.

Experiment 1: norming study of verb bias in Mandarin

Method

Participants

We recruited 404 native Mandarin speakers for the online tests. The tests were shared on several social platforms (e.g., Wechat or QQ) to reach our target group of university students from China. They used Mandarin as a dominant language in their daily life. We excluded 37 participants who did not follow the instruction to describe the target pictures (i.e., writing numbers or other content unrelated to the target pictures), leaving a final sample of 367 participants. Most participants (75%) came from Guangdong Province and the rest (25%) came from the other 19 Provinces or Municipalities of China.

Materials

We selected 48 single-character dative verbs from the corpus SUBTLEX-CH (Chinese Word and Character Frequencies; Cai & Brysbaert, 2010). The alternation verb bias, DO vs. PO, was measured in a picture description task (Bernolet & Hartsuiker, 2010). For each verb, three entities were used to construct a picture of a ditransitive event involving an agent, recipient, and theme. There were two versions of these pictures with different positions of recipient and theme (see Figure 1; these were the same materials as used by Huang et al., 2016). Similar to Arai et al. (2007), the three entities did not express an action (i.e., they were static), allowing participants to construct the verb-relating event flexibly. These 48 verbs were divided into 2 parts, so that there were 24 verbs for each version of the test and 2 versions for each verb. Thus, we had four versions of the online test.

Figure 1

Example of picture description task in the testing of verb bias

Note. “Version A” on the left presents the theme on the right, and the potential agent or recipient on the left and in the middle. “Version B” presents the theme in the middle, and the potential agent and recipient on the left or right. The verb underneath the three entities “送” means “give”.

Procedure

Participants were instructed to describe the picture with one sentence in Mandarin using the provided verb (Bernolet & Hartsuiker, 2010). Responses were provided in the written modality. The test took around 10 minutes.

Scoring

We coded all responses as DO, PO, or others. If a verb was followed by the recipient and then the theme, we coded it as DO. If a verb was followed by the theme and then a preposition and recipient, we coded it as PO. Otherwise, we coded the responses as others.

Results

We collected 8564 valid responses for the 48 items, with 846 responses coded as DO (9.88%), 1791 responses coded as PO (20.91%), and 5927 responses coded as others (69.21%). The verb bias was computed as the log-odds for the valid response of DO or PO structure (Bernolet & Hartsuiker, 2010; Jaeger & Snider, 2008). A negative value indicates the verb has a PO-bias and a positive value indicates it has a DO-bias. These 48 verbs showed a strong preference for the PO structure on average (Mean = -1.47, SD = 1.34) (see Figure 2). Over 85% of verbs were PO-biased, 8 verbs were extremely PO-biased without any DO responses, and only 7 verbs were DO-biased with slightly more DO than PO responses. Based on this distribution of verb bias in Mandarin, we

chose four DO-biased verbs (Mean=0.92, SD=0.40) and four PO-biased verbs (Mean=-2.01, SD=0.34) for the prime sentences, and four neutral-biased (slightly PO-biased) verbs (Mean=-0.22, SD=0.12) for the target sentences (see Table 1). It is important to note that even though we chose verbs that were strongly biased (especially the PO-biased verbs), each verb can in principle occur with both DOs and POs and that indeed, both DOs and POs were attested in our data set for each selected verb.

Due to the flexibility of description for the target pictures (i.e., participants were not instructed to use the classical ditransitive structures (DO or PO) to describe the pictures), we found a high proportion of other responses, which is similar to the corpus data of Dutch newspapers (e.g., 74.7% other responses, see Coleman, 2006, 2009; Coleman & Bernolet, 2013). The second reason for the high proportion of other responses is that Mandarin dative verbs have more than two structural options to describe the target pictures. For example, these other responses involved shifted dative structures (e.g., shifted PO, “wangzi gei xinniang song le jiezhi”, “the prince to the bride gives a ring”; or BA-DO, “wangzi ba jiezhi song geile xinniang”, “the prince BA a ring gives the bride”), active or passive sentences, and even relative clauses. These responses may result from the flexible word order of Mandarin Chinese (C. N. Li & Thompson, 1989; P. Li, 1996; P. Li et al., 1993; W. Zhang, 1991). However, the basic word order of dative structures in Mandarin Chinese is still “[V NP NP]” or “[V NP PP]”, which differs from shifted dative structures (Man, 2003). Thus, we coded the latter responses as other responses.

Figure 2

Distribution of the structure bias of 48 dative verbs in Mandarin

Note. Structural bias of verbs was calculated as the logarithm of the frequency of the DO structure following the verb divided by the frequency of the alternative PO structure (i.e., “ $\log[(\#DO+1)/(\#PO+1)]$ ”, with 1 added to both operands to avoid division by zero). Values larger than 0 indicate a DO-bias (i.e., white circle) and values below 0 indicate a PO-bias (i.e., black circle). The red line in the middle represents the mean value (-1.47) of all 48 dative verbs.

Table 1

Frequency of DO and PO responses and alternation bias of 48 dative verbs.

Verb	Response frequencies			Verb bias	Verb	Response frequencies			Verb bias
	DO	PO	Others			DO	PO	Others	
做(make)	0	64	115	-4.17	派(send)	4	27	146	-1.72
抓(catch)	0	38	137	-3.66	捎(bring along)	10	55	110	-1.63
捉(catch)	0	35	144	-3.58	留(leave)	8	44	131	-1.61
捡(pick up)	0	30	147	-3.43	汇(transfer)	11	55	114	-1.54

摘(pick)	1	56	123	-3.35	寄(post)	17	55	103	-1.13
找(find)	0	17	166	-2.89	扔(throw)	10	32	136	-1.10
提(carry)	2	50	125	-2.83	租(rent)	6	19	154	-1.05
拉(drag)	2	42	134	-2.66	分(divide)	19	54	101	-1.01
抬(lift)	0	11	167	-2.48	卖(sell)	14	36	128	-0.90
投(throw)	2	34	141	-2.46	抛(throw)	26	56	98	-0.75
丢(throw)	2	33	140	-2.43	让(offer)	15	31	132	-0.69
倒(pour)	1	21	156	-2.40	借(borrow)	19	29	134	-0.41
捧(hold)	2	31	149	-2.37	递(pass)	33	49	102	-0.39
买(buy)	3	40	135	-2.33	配(assign)	18	24	140	-0.27
拣(pick up)	2	29	150	-2.30	赠(gift)	46	59	72	-0.24
拿(take)	7	75	94	-2.25	还(return)	43	49	86	-0.13
捐(donate)	8	73	97	-2.11	赔(compensate)	53	60	69	-0.12
转(transfer)	5	45	129	-2.04	送(give)	82	58	38	0.34
写(write)	3	29	145	-2.01	交(hand)	33	23	121	0.35
订(order)	3	28	147	-1.98	收(receive)	14	7	156	0.63
搬(move)	0	6	172	-1.95	抢(rob)	7	3	165	0.69
叫(order)	0	6	171	-1.95	赏(grant)	107	39	32	0.99
退(refund)	3	26	149	-1.91	授(reward)	83	26	70	1.13
发(send)	7	49	122	-1.83	赐(award)	115	33	34	1.23

Note. The verbs in italic were chosen as the prime or target verbs in Experiment 2. PO-biased prime verbs included “丢(throw)”, “捐(donate)”, “退(refund)” and “留(leave)”. DO-biased prime verbs included “送(give)”, “赏(grant)”, “授(reward)” and “赐(award)”. Neutral-biased target verbs included “递(pass)”, “赠(gift)”, “还(return)” and “赔(compensate)”.

Discussion

We observed a strong overall PO structure preference in Mandarin Chinese (i.e., 846 DO vs. 1791 PO responses, thus 68% PO responses overall). This PO-bias is comparable to that observed in the intransitive baseline conditions of Mandarin structural priming in production experiments (i.e., 65% in Z. Cai et al., 2012; 70% in Chen et al., 2019). Such production experiments were highly constrained to elicit dative responses with a preamble and a target picture

(e.g., “The policeman gave”) and therefore there were hardly any other responses. The alternation biases obtained here, in contrast, reflect Mandarin dative structural preferences in more spontaneous production.

In the experiment below, we presented selected verbs with either a DO- or PO-bias, in order to test whether: 1) there is abstract structural priming in Mandarin sentence comprehension; 2) this priming is sensitive to prediction error.

Experiment 2: inverse preference priming in comprehension

Method

Participants

We paid 72 native Mandarin speakers 10 euros to participate in Experiment 2. They were postgraduate students or postdoctoral researchers at Ghent University from all over China. All reported to have normal or corrected-to-normal vision. The study was approved by the ethics committee of the Faculty of Psychology and Educational Sciences, Ghent University.

Materials

We constructed 48 sets of materials (see <https://osf.io/6kcyz/> for the full list). Each set included four prime sentences (DO-biased DO, DO-biased PO, PO-biased DO, and PO-biased PO, see Table 2), and two ditransitive target sentences (PO and DO) with neutral-biased verbs. We chose the theme and recipient nouns in the target sentences so that there was a temporary ambiguity in the first syllable of the first noun phrase (NP1) (e.g., “*Qiuyuan* [football player]” and “*Qiupai* [racket]”, see Table 2; this was the same manipulation as used by Branigan et al., 2018). Therefore, the sentence remained ambiguous between a DO and PO from the onset of the target verb to the onset of the second syllable of NP1.

Table 2

Example of one set materials in Experiment 2

Conditions	Example
<i>Prime sentences</i>	

a. DO-biased DO	<i>Wujing song Tegong yiba shouqiang.</i>
The policeman gives the spy a gun.
b. DO-biased PO	<i>Wujing song shouqiang gei Tegong.</i>
The policeman gives a gun to the spy.
c. PO-biased DO	<i>Wujing diu Tegong yiba shouqiang.</i>
The policeman throws the spy a gun.
d. PO-biased PO	<i>Wujing diu shouqiang gei Tegong.</i>
The policeman throws a gun to the spy.

Target sentences

DO	<i>Yeye huan Qiuyuan yifu Qiupai.</i>
The grandpa returns the football player a racket.
PO	<i>Yeye huan Qiupai gei Qiuyuan,</i>
The grandpa returns a racket to the football player.
-

We then divided the 48 sets of materials into 8 lists in a Latin Square design. Each list included 12 prime sentences in each of the four prime conditions. Half of the target sentences had a DO structure and the other half a PO structure, which were counterbalanced for each prime sentence. Additionally, there were three versions of each list to balance orders of the positions of the entities in the target pictures. This was done to balance out effects of spatial expectations of upcoming words (see Figure 3). Additionally, we constructed 96 fillers with a range of sentence structures (e.g., active, passive, shifted-PO, Ba-construction). Half of the fillers also contained homophonic syllables in audio sentences. One half of the fillers had the same structure for the pair of visual and audio sentences and the other half did not. In order to cover up the purpose of this priming study, one third of the filler trials required participants to recall the pictures that they saw in the previous screen and describe the pictures with their own words. To make this cover task more challenging, half of the filler pictures involved one entity that was incongruent with the corresponding audio sentences, and the other half did not. All 144 trials were presented in a

pseudo-random order.

Figure 3

Example target picture in Experiment 2

Note. Participants heard DO or PO target sentences (see Table 2) while they saw the corresponding target picture. Version A on the left presents the theme (“racket”) on the top, the recipient (“football player”) on the left, and the agent (“grandpa”) on the right; so the order from top to left to right was “T-R-A”. Version B in the middle represents the order “A-T-R” and Version C on the right presents the order “R-A-T”.

Procedure

We used the visual world and structural priming paradigm (Arai et al., 2007). Before the experiment, participants were required to memorize all the entities that were used in the targets and they only began the experiment after they correctly named these entities. During the experiment, participants were instructed to focus on the fixation point so that a drift-correction was triggered. Next, participants read the prime sentence aloud and then pressed the spacebar to trigger the corresponding target picture. They had 1500ms to preview the picture. Then, they listened to the audio sentence carefully and watched the target picture at the same time. If they saw ‘recall’ after target picture presentation (i.e., on 1/3 of the filler trials), they needed to describe the target picture correctly with their own sentence (but note that they mostly repeated the sentences that they just heard verbatim, or in the case of pictures with one mismatching entity, near-verbatim). We recorded the right eye of participants from onset to 350ms post-offset of audio sentences by using a SR-Research EyeLink-1000. The sampling rate was 1000Hz. Participants sat 70 cm from the screen and they usually took about 1 hour to finish this experiment.

Time windows

Similar to Thothathiri and Snedeker (2008a), we analyzed eye-movements in the time window of NP1 (e.g., “*Qiupai* (racket)” or “*Qiuyuan* (football player)”). However, processing the

verb (e.g., “huan (returns)”) is enough for comprehenders to engage in prediction about structure (Arai et al., 2007). Therefore, we constructed two critical ambiguous time windows: the *target verb window* (1000ms) from 200ms (200ms after the onset of the target verb, following Matin et al., 1993; Thothathiri & Snedeker, 2008a) to 1200ms (200ms after the onset of the first syllable of NP1, “Qiu”); and the *first syllable of NP1 window* (550ms) from 1200ms to 1750ms (200ms after the onset of second syllable of NP1, “yuan” or “pai”).

Data analysis

We recorded the fixation time within a rectangular region of interest around the corresponding entities (e.g., agent, recipient, theme) for the target trials. The corresponding visual item to the ambiguous noun phrase were the animate recipient (e.g., “Qiuyuan [football player]”) and the inanimate theme (e.g., “Qiupai [racket]”). We then calculated the proportion of looks to these two items within the two ambiguous time windows, because looks to the recipient after verb onset indicated the prediction of DO structure, whereas looks to the theme indicated PO structure. We used the empirical logit transformation (Barr, 2008) to calculate the gaze probability data of recipient and theme. Then we computed the dependent variable as the difference score of gaze probability between recipient and theme (Thothathiri & Snedeker, 2008a).

The two critical ambiguous time windows were analyzed with linear mixed models using the “lme4” package (Bates & Maechler, 2009) in R, with the main effect of two variables (verb bias and structure of primes) and their interaction effect as the predictors. Due to model convergence issues (Barr et al., 2013), we reduced the random effect structure with an intercept for subjects, and a slope of the interaction and intercept for items in the LME model for the target verb time window; and the random effect structure with a slope of structure and intercept for subjects, and a slope of verb bias and intercept for items in the LME model of the time window of the first syllable of NP1. In order to analyze the time course of the structure prediction within each time window, we used the method of cluster-based permutation analysis (Barr et al., 2014; Borovsky et al., 2016; Maris & Oostenveld, 2007; Weighall et al., 2017). We implemented the permutation test with the “permuco” package in R (Frossard & Renaud, 2019). We tested two main effects and one corresponding interaction effect of two factors (verb bias and structure) with a full random structure for subjects (by-subject analysis) or items (by-item analysis) in each time bin (50ms) when controlling the family-wise error rate. We used F tests with a threshold of $p < .05$

(two sided), 5000 permutations, and the sum as a *clustermass* statistic, to detect when the structure prediction began and ended within the ambiguous time windows. Data and scripts are available online: <https://osf.io/6kcyz/>.

Results

Traditional time-window analysis

Figure 4A shows the time course of eye-movement data from the onset of the target verb during comprehension of target sentences after primes with different structures (DO vs. PO). We found a significant main effect of structure within both the time window of the target verb (e.g., ‘*huan*’) ($\beta = .52$, $SE = .18$, $t = 2.96$, $p < .01$) and the first syllable of NP1 (e.g., ‘*Qiu*’) ($\beta = .80$, $SE = .23$, $t = 3.44$, $p < .001$). The time course graph illustrates a clear priming effect with a larger proportion of looks to recipients after DO primes than PO primes in both ambiguous time windows. Figure 4B splits out the prime conditions for verb bias and suggests that bias modulates the priming effect. Indeed, the interaction between structure and verb bias was significant in the time window of the first syllable of NP1 ($\beta = -.95$, $SE = .45$, $t = -2.11$, $p < .05$) (see Figure 5B), but it was not significant in the time window of the target verb ($\beta = -.22$, $SE = .37$, $t = -.60$, $p > .1$) (see Figure 5A). There was no main effect of verb bias ($p > .1$). Furthermore, in the time window of the first syllable of NP1 (see Figure 5B), the proportion of looks to the recipient was larger after PO-biased verbs followed by DO primes than PO primes ($\beta = 1.27$, $SE = .32$, $t = 3.94$, $p < .001$). The similar priming effect did not occur in DO-biased verbs ($p > .1$). The proportion of looks to the recipient was marginally larger after PO-biased DO primes than after DO-biased DO primes ($\beta = .58$, $SE = .32$, $t = 1.80$, $p = .07$). There was no inverse preference priming effect in the PO primes ($p > .1$).

Cluster-based permutation analysis for eye-tracking data

For the main effect of structure, the permutation analysis indicated two significant clusters in the target verb window: a cluster from 550ms - 850ms (*cluster-mass* = 37.15, $p < .05$, for a by-subject analysis, see Figure 4A) or from 550ms - 900ms, *cluster-mass* = 59.64, $p < .05$, for a by-item analysis); and the other is from 950ms - 1200ms (*cluster-mass* = 35.36, $p < .05$, for the by-subject analysis; *cluster-mass* = 31.34, $p = .046$, for the by-item analysis). Additionally, the analysis showed one significant cluster in the time window of the first syllable of NP1 from 1200ms - 1750ms (*cluster-mass* = 88.87, $p < .01$, for the by-subject analysis) or from 1300ms - 1750ms (*cluster-mass* = 68.74, $p < .01$ for the by-item analysis). For the interaction between

structure and verb bias, the results only showed one significant cluster from 1550ms - 1750ms ($cluster-mass = 20.30, p < .05$, for the by-subject analysis, see Figure 4B; $cluster-mass = 31.43, p < .05$, for the by-item analysis) in the NP1 window. There was a small cluster (from 600ms - 650ms in the by-item analysis, or from 500ms - 650ms in the by-subject analysis) in the target verb window, but it was not significant ($p > .1$). Importantly, the significant cluster of the interaction (1550ms - 1750ms) showed a similar pattern as the whole time window (Figure 5B). Within this cluster, the priming effect occurred in PO-biased verbs ($\beta = 1.44, SE = .35, t = 4.09, p < .001$) but not for DO-biased verbs ($p > .1$), and the inverse preference priming also occurred in DO primes ($\beta = .79, SE = .36, t = 2.22, p < .05$) but not in PO-primes ($p > .1$).

Figure 4

Difference in proportion of looks to recipient and theme for each time bin (50ms) from onset of target verb.

Note. The time window of verb is from 200ms to 1200ms and the time window of the first syllable of the first noun phrase is from 1200ms to 1750ms. Plot A on the top indicates the difference in the proportions of looks to recipient (predicting DO structure) and to theme (predicting PO structure) after prime sentences with different structure (DO vs. PO); the grey rectangles within the time windows indicate the clusters where the main effect of structure was significant (by-subject analysis). Plot B on the bottom indicates the difference in the proportions of looks to recipient and theme after prime sentences with different structure (DO vs. PO) and prime verbs with different structure bias (DObias vs. PObias); the grey rectangles in the time window of the first syllable of the first noun phrase indicates the cluster where the interaction effect between structure and verb bias was significant (by-subject analysis).

Figure 5

Difference of gaze probability between recipient and theme for prime conditions with different structures (DO vs. PO) and verb bias (DObias vs. PObias) in two critical time windows.

Note. Plot A on the left indicates the interaction between structure and verb bias in the time window of target verb ($p > .1$). Plot B on the right indicates the interaction between structure and verb bias in the time window of the first syllable of the first noun phrase ($p < .05$). The error bars reflect standard errors from a by-participant analysis.

Discussion

This experiment demonstrated abstract structural priming in comprehension. Interestingly, the main effect of structure was already significant in the time window of the target verb, suggesting that the priming effect started soon after the onset of the target verb (see Figure 4A). As predicted by the implicit learning account, there was an inverse preference priming effect in Experiment 2 during the process of language comprehension, similar to that in production (Jaeger & Snider, 2013). The interaction between structure and verb bias was significant in the time window of the first syllable of NP1 (see Figure 5B), consistent with Fine and Jaeger's (2013) reanalysis of Thothathiri and Snedeker's (2008a) comprehension study. This finding suggested that structure prediction in comprehension was modulated by the structure bias of the verbs. The inverse preference effect occurred with PO-biased prime verbs (i.e., primes with PO-biased verbs followed by the unexpected DO structure elicited more looks to recipients than when followed by the expected PO structure), but it did not occur in DO-biased verbs. One reason might be that the structure bias of PO-biased verbs is much larger than that of DO-biased verbs (i.e., -2.01 vs. 0.92), resulting in much larger prediction error for PO-biased verbs. This asymmetry is consistent with the results of a Dutch production study (Bernolet & Hartsuiker, 2010). Dutch has a similar

distribution of structure bias for ditransitives as Mandarin. Bernolet and Hartsuiker found that the strongest DO priming effect was induced by the strongest PO-biased verb (i.e., -1.63) and that the strength of the priming effect size linearly decreased with decreasing PO bias of the prime verb. In contrast, the PO priming effect with DO-biased verbs (i.e., 0.27) was much smaller than the DO priming effect with PO-biased verbs, and PO priming did not interact with the DO bias of the prime verb. Together, these findings suggested an error-based prediction system, in that larger prediction errors (related to the structure bias of the specific prime verbs) triggered a stronger priming effect.

General Discussion

In Experiment 1, we collected data from 367 Mandarin speakers to norm 48 dative verbs and found a strong PO bias overall. Then in Experiment 2, we manipulated the structure bias of prime verbs (verb bias) and prime structure in a visual-world eye-tracking study. First, we found stable structural priming in comprehension for Mandarin speakers even though the verbs were different between prime and target. In particular, comprehenders showed a higher proportion of looks to an animate recipient than to an inanimate theme when they heard the target sentence after a DO prime, and a higher proportion of looks to the inanimate theme than to the animate recipient after a PO prime. Structural priming occurred in both the time windows of the target verb and of the first syllable of the first noun phrase. Second, the structural priming effect was modulated by verb bias, so that structural priming was inversely related to the structure bias of prime verbs. This inverse preference effect occurred in the time window of the first syllable of the first noun phrase. Specifically, priming was stronger after a DO prime with a verb biased towards the alternative structure (i.e., PO-bias) than with a verb biased towards the same structure (DO-bias). However, the inverse preference effect seemed to depend on the strength of the bias, with weaker priming when there was a weak structure bias (i.e., DO-biased verbs).

The abstract structural priming suggested that the prediction for upcoming structure in the target sentences was shared with previously experienced prime sentences, supporting a lexically independent representation of structure in comprehension, as is the case for production. This result replicates Thothathiri and Snedeker's (2008a, 2008b) findings in comprehension. Different from Thothathiri and Snedeker's studies, we only presented one prime sentence before the target

sentence and nevertheless found structural priming, indicating that one prime is enough to yield abstract structural priming in comprehension (as is also true of production). Our finding differs from Arai et al. (2007) who did not find abstract structural priming, even though we used the same comprehension task. Ziegler and Snedeker (2019) suggested that the absence or presence of abstract priming depends on task demands. They argued that the task Arai et al.'s used requires little need to continuously predict the structure of the target sentences, because once comprehenders have heard the agent and target verb, they can easily identify the two post-verbal arguments (e.g., the animate entity is likely to be the recipient and the inanimate entity the theme). Additionally, the participants had ample time to access the concepts of all arguments during the 1500ms preview after target picture onset. Given these task characteristics, there would be no need to predict structure. In contrast to this task-demand hypothesis, our findings suggested that comprehenders are in fact continuously predicting structural information of the target sentences in this task. We propose another interpretation of the absence of abstract structural priming in Arai et al.'s study. These authors did not strictly control the structure bias of the prime and target verbs, which may have confounded any priming effects. If the target verbs are relatively strongly biased towards either the DO or PO, there is little room for priming effects (see Bernolet & Hartsuiker, 2010; Coyle & Kaschak, 2008).

Importantly, when we manipulated verb bias and prime structure together in comprehension, we found an inverse preference priming effect. This finding indicated that structure prediction in comprehension is sensitive to the prediction error (i.e., larger prediction error triggered a stronger priming effect), in line with the hypothesis from the implicit learning account (Chang et al., 2006). Our findings are consistent with Fine and Jaeger's (2013) results: these authors observed inverse preference priming when comprehenders processed the first of two prime sentences but not when they processed the second prime sentence, presumably because comprehenders rapidly adapted to the unexpected structure in the first prime and then were less surprised by such a structure in the second prime. Additionally, the inverse priming effect in comprehension we observed here was on the basis of prediction errors in a task where the prime sentences were read aloud, which generalized Thothathiri and Snedeker's findings in a task where the prime sentences were comprehended in the auditory modality. Similarly, the inverse preference priming effect also occurred in production regardless of whether the prime sentences were only produced or comprehended (Bernolet & Hartsuiker, 2010; Jaeger & Snider, 2013; Peter et al.,

2015). Together, these findings support a cross-modality error-based prediction system serving both production and comprehension.

There are several alternative accounts that interpret structural priming with respect to residual activation of syntactic representations (Pickering & Branigan, 1998) or shared representations of information structure (Prat-Sala & Branigan, 2000). However, these accounts cannot easily explain the inverse preference priming effects. According to Reitter et al. (2011), the residual activation model would predict a *preference* priming effect rather than an inverse preference effect, because the more strongly biased structure more strongly activates the structure representation in the processing of prime sentences, resulting in higher resting activation. In contrast, the information-structure account predicts an overall priming effect when the order of thematic roles are shared or the entity is emphasized (Griffin & Weinstein-Tull, 2003), which would not be modulated by the structure bias of verbs. Together, our findings supported the prediction of implicit learning accounts, that “structural priming is a form of error-based implicit learning, with the same learning mechanism responsible for syntax acquisition and for priming” (see Chang et al., 2006, pp. 245-246).

However, abstract structural priming in comprehension does not always seem to be accompanied with a verb bias effect. In Experiment 2, structural priming occurred in the time window of the target verb but the inverse preference priming did not. This finding cannot be explained by the implicit learning account, which predicts that priming effects would be tied to inverse preference priming, because both effects would occur as a result of weight changes in response to prediction error during prime sentence processing, leading to an altered bias for either the DO or PO. It is not obvious why part of this altered bias would surface in both time windows, but another part of the bias only during the later time window. One possibility might be that, in contrast to an implicit learning account, the inverse preference effect and the basic priming effect have different loci in the system. In the literature on structural priming in production, some authors have argued for a role of both implicit learning and explicit memory effects, even in abstract structural priming (e.g., Bernolet et al., 2016). A less interesting possibility, which cannot be ruled out, however, is that the magnitude of the inverse preference effect is simply much smaller than that of the basic priming effect. As a result, any such effect may have been strongly affected by noise in the data and remain undetected in the early time window of the target verb. One way to minimize the interference of noise in the early time window and to further investigate the

possibility that both abstract priming and the inverse preference effect have the same time course, might be to investigate inverse preference in a language with a larger range of verb biases. For instance English, with both strongly DO-biased and PO-biased dative verbs, allows for the manipulation of strong verb bias mismatch conditions in both DO and PO prime sentences.

A final important finding is the generalization of abstract structural priming in comprehension to Mandarin. Because of the language properties of Mandarin (i.e., flexible word order and a lack of markers for morphophonology, see P. Li, 1996 and P. Li et al., 1993), many studies proposed a language-specific hypothesis for Mandarin, according to which semantic processing precedes syntactic processing in comprehension (Wang et al., 2013; Yang et al., 2009; Y. Zhang et al., 2010, 2013). These studies rarely showed an early sensitivity to violations of word category (e.g., ELAN effect), in contrast to studies in English. Instead, they showed difficulties with semantic integration (e.g., N400 effect; Zhou et al., 2009). However, we observed structure prediction effects for Mandarin comprehenders, even though in general they may have difficulties to predict syntactic information consistently. Why do the priming and EEG studies in Mandarin lead to different conclusions? One interpretation is that Mandarin comprehenders can predict structure information independently after they successfully access the concepts of the post-verbal arguments in the sentence (based on visual object recognition in the visual-world paradigm), but not when they have no access yet to the concepts (as many EEG studies did not find any early prediction effects of syntax in violation conditions of both semantics and syntax, see Wang et al., 2013). For future studies, it would therefore be interesting to investigate whether Mandarin comprehenders can predict structure information before they can access the concepts of post-verbal arguments. In particular, can comprehenders still make a syntactic prediction when the semantic prediction can also help them to solve the ambiguity in language processing?

Our finding of an error-based structure prediction effect in Mandarin Chinese is consistent with the findings in some Indo-European languages (i.e., Dutch and English, see Bernolet & Hartsuiker, 2010; Fine & Jaeger, 2013; Jaeger & Snider, 2013), suggesting a similar mechanism for different languages. In the view of implicit learning (Chang et al., 2006), speakers or comprehenders predict structure based on a shared representation of languages, which starts from their first language learning. Therefore, it suggests that inverse preference priming effects should occur between languages for multilinguals. Indeed, many studies of bilinguals and multilinguals demonstrated that priming effect occurs across languages (e.g., English, French, and Dutch in

Hartsuiker, Beerts, Loncke, Desmet, & Bernolet, 2016; and German and English in Kidd, Tennant, & Nitschke, 2015; see Van Gompel & Arai, 2018, for a recent review). But it remains to be seen whether this between-languages structural priming depends on an error-based prediction mechanism as in within-languages processing. On one scenario it should not, as a prediction error related to Language X is not informative about the distribution of structures in Language Y. Therefore, an interesting research question for the future is whether the inverse preference priming effect occurs between different languages.

In conclusion, we performed a norming study to create a valuable resource for further studies: bias information for 48 dative verbs in Mandarin. In the following comprehension study, we found structural priming in the absence of verb repetition, suggesting that abstract structural representation is involved in comprehension as it is in production. Moreover, we found that the abstract priming was modulated by structural bias of prime verbs. This finding supports the hypothesis of an error-based prediction mechanism for structural priming, as proposed by the implicit learning theory.

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