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The published version contained some errors in how Verb Surprisal was calculated. This version (soon to be posted in BLC) contains the correct values. Supplementary materials are available at the end of this document.

Running-head: Priming and adaptation

Priming and adaptation in native speakers and second-language learners*

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Keywords: syntactic priming, adaptation, second language processing, error-based learning

Native speakers show rapid adjustment of their processing strategies and preferences on the basis of the structures they have recently encountered. The present study investigated the nature of priming and adaptation in second-language (L2) speakers and, more specifically, whether similar mechanisms underlie L2 and native language adaptation. Native English speakers and Korean L2 learners of English completed a written priming study probing the use of double object and prepositional phrase datives. Both groups showed cumulative adaptation effects for both types of dative, which was stronger for the structure that was initially less frequent to them (prepositional phrase datives for the Native English speakers, and double object datives for the L2 learners). This supports models of priming that incorporate frequency-based modulation of long-lasting activation of structures. L2 learners and native speakers use similar processing mechanisms; differences in adaptation can be accounted for by differences in the relative frequency of structures.

Keywords: syntactic priming, adaptation, second language processing, error-based learning

Native speakers continuously adjust their language comprehension and production to the properties of the language they encounter around them. For instance, listeners quickly adjust to a speaker's accent (e.g., Kraljic, Samuel, & Brennan, 2008), take over their interlocutor's way to refer to objects (e.g., Brennan & Clark, 1996; Brennan & Hanna, 2009), or re-use the syntactic structure they just encountered (e.g., Bock, 1986). One mechanism that has been proposed for this adjustment is error-based learning, which is a form of implicit learning (Chang, Dell, & Bock, 2006). Under error-based learning, the language user generates predictions concerning the upcoming language input. When these predictions are not borne out, the user's knowledge is updated. This mechanism has also been proposed to underlie first language acquisition (Chang et al., 2006). Evidence for error-based learning has been obtained from both adult native language users (Farmer, Fine, Yan, Cheimariou, & Jaeger, 2014; Jaeger & Snider, 2008; Jaeger & Snider, 2013) and first-language learners (Peter, Chang, Pine, Blything, & Rowland, 2015). However, the role of error-based learning in late second-language (L2) processing and learning is not clear. On the one hand, studies on advanced L2 learners suggest that these learners can use information predictively during language processing (Foucart, Martin, Moreno, & Costa, 2014; Hopp, 2013). On the other hand, L2 learners seem to be resistant to adaptation: even advanced L2 learners do not appear to adjust their preferences even though they receive ample evidence from the input that their current knowledge is incorrect (Arnon & Ramscar, 2012; Hopp, 2015). Investigating to what extent L2 learners adapt to the language context and what the mechanisms are underlying such adaptation, if attested, may therefore provide insight in how L2 learners can use the language they encounter to shift their knowledge and processing in the direction of the target language.

The present study investigates adaptation in L2 learners through a syntactic priming paradigm. Syntactic (or structural) priming is the tendency to re-use, or expect, a previously encountered syntactic construction (e.g., Arai, van Gompel, & Scheepers, 2007; Bock, 1986; Ferreira & Bock, 2006; Ledoux, Traxler, & Swaab, 2007). For instance, after encountering a prepositional object ditransitive (PO), e.g., *The girl gave the ball to the boy*, native speakers of American English are more likely to use the PO construction in their own utterance than the double object ditransitive alternate (DO), e.g., *The girl gave the boy the ball*. We will use the term IMMEDIATE PRIMING to refer to priming in response to a structure just encountered. Priming can also be cumulative, that is, a structure that has been encountered often in the context tends to be produced more often (Kaschak, 2007; Kaschak & Borreggine, 2008; Kaschak, Kutta, & Jones, 2011; Kaschak, Loney, & Borreggine, 2006), or becomes easier to parse (Farmer et al., 2014; Fine & Jaeger, 2016; Fine, Jaeger, Farmer, & Qian, 2013), regardless of whether the immediately preceding trial contains that structure. We will use the term CUMULATIVE ADAPTATION to refer to the latter type of priming. Immediate priming and cumulative adaptation effects have been observed in both production and comprehension. This has been taken as an argument that similar mechanisms are operational in production and comprehension priming, although production and comprehension priming may differ in the size of the priming effects, and in the effect of lexical repetition between prime and target (see for an overview, Tooley & Bock, 2014). In the current study we investigate priming in production only.

Priming and adaptation in native speakers

In native speakers, priming effects are modulated by fine-grained experience. Typically, an inverse frequency interaction is observed: structures that are used infrequently in the language typically show larger priming effects than their more frequent alternates (e.g., Hartsuiker & Westenberg, 2000; Jaeger & Snider, 2008; Jaeger & Snider, 2013; Scheepers, 2003). This holds for abstract structures (e.g., PO ditransitives being less frequent than DO ditransitives in American English), as well as finer-grained representations such as those based on the bias of verbs or nouns. For instance, if a prime trial has a structure that is infrequent given the biases of the prime verb, priming is typically larger than when the prime has a structure that the verb is heavily biased towards (Bernolet & Hartsuiker, 2010; Fine & Jaeger, 2013; Jaeger & Snider, 2008; Jaeger & Snider, 2013). This effect is known as SURPRISAL (Jaeger & Snider, 2008). Frequency effects based on long-term experience with the language can be modulated by the short-term exposure to the context of the experiment or dialogue. When the experimental context or dialogue contains sentences of a particular structure, the participants or interlocutors are more likely to produce or expect this structure as they are increasingly exposed to this structure over time (e.g., Fine et al., 2013; Jaeger & Snider, 2008; Kaschak, 2007). This adaptation effect is largest for structures that are initially infrequent (Fine et al., 2013; Hartsuiker & Westenberg, 2000). This cumulative effect may affect the size of the immediate priming effects: priming of initially infrequent structures is larger at the beginning of the study compared to when the participant has been exposed to these structures many times over the course of the experiment (Hartsuiker & Westenberg, 2000). Whether the same mechanisms underlie immediate priming and cumulative adaptation is still a matter of debate, although recent evidence

suggests commonalities (Fine & Jaeger, 2016). Both immediate and cumulative priming phenomena can be accounted for in terms of error-based learning. Based on experience, the language user predicts upcoming information (Chang et al., 2006). For instance, given the verb and its subcategorization biases, the next constituent can be predicted. If this prediction is not borne out (i.e., prediction error), the knowledge is adjusted, which in turn affects future expectations. The degree of adjustment is dependent on the size of the prediction error: the more the actual input deviates from the expected input, the larger the adjustment. This accounts for the inverse frequency and surprisal effects, as well as the longer-term adaptation over the course of the experiment (Chang et al., 2006).

Alternative models have been proposed in which priming is driven by mechanisms other than error-based learning. For instance, in a Residual Activation approach to structural priming (e.g., Pickering & Branigan, 1998), the representations of verbs and other lexical items are connected to abstract structural representations. The lexical information in the prime activates the structural information it is connected with. This activation lingers, making it more likely that the prime structure is re-used in the target. This is especially the case when the same lexical items are used in the prime and target (this is known as the lexical boost effect, that is, the observation that priming is larger when the prime and target share lexical items than when they do not, e.g., Cleland & Pickering, 2003; Pickering & Branigan, 1998). Under the Residual Activation approach, lexical-independent structural priming and the lexical boost effect are dealt with in the same way. A problem for this approach is that lexical boost effects have been shown to be shorter lasting than lexically-independent priming effects, which suggests that different mechanisms underlie these effects (Hartsuiker, Bernolet, Schoonbaert,

Speybroeck, & Vanderelst, 2008). In addition, since the residual activation is assumed to be only transient in nature, this model fails to account for longer-lasting and cumulative priming effects. Reitter, Keller and Moore (2011), on the other hand, propose an ACT-R based model according to which priming can be seen as, first, a learning mechanism adjusting the base-activation of abstract structures in long-term memory, and, second as a lexically-based association mechanism, responsible for short-term priming and the lexical boost effect (for other dual-mechanism accounts, see Hartsuiker et al., 2008; Tooley & Traxler, 2010). This model can account for inverse frequency interaction: the adjustment of the base-activation is larger for infrequent than for frequent structures. However it is unclear how this model, or the Residual Activation approach, can account for prime verb surprisal effects (Fine & Jaeger, 2013).

Priming and adaptation in language learners

If syntactic priming and adaptation effects depend on previous experience, we expect priming effects to be different in learners of a language compared with more experienced users of the language in question. Indeed, priming studies in children (Messenger, Branigan, & McLean, 2011; Peter et al., 2015; Rowland, Chang, Ambridge, Pine, & Lieven, 2012) reported larger syntactic priming effects in 3- to 4-year-olds than in older children and adults. Children showed priming effects regardless of whether lexical items were repeated between prime and target, suggesting they dispose over abstract syntactic forms early in their language development (Peter et al., 2015; Rowland et al., 2012; but see Savage, Lieven, Theakston, & Tomasello, 2006). Furthermore, children showed

larger surprisal effects than adults (Peter et al., 2015). Peter et al. accounted for the larger surprisal effects by assuming that children are still establishing verb biases. Initially children have a large learning rate, allowing for large changes. Changes become smaller in magnitude later in the learning process in order to stabilize the knowledge and to prevent new information from continuously overwriting old information.

In contrast to first language (L1) learners, late L2 learners show larger within-L2 priming effects with increasing proficiency (Bernolet, Hartsuiker, & Pickering, 2013). L2 learners can develop native-like priming effects in their L2 (Flett, Branigan, & Pickering, 2013; Gries & Wulff, 2005), and can even show immediate priming effects for structures that do not exist in their L1 (Flett et al., 2013; Shin & Christianson, 2012). In addition, syntactic priming effects are larger when words are repeated between the prime and the target, at least in lower-proficiency L2 learners (Bernolet et al., 2013; Y. Kim & McDonough, 2008; Matsumoto & Yamashita, 2006; Schoonbaert, Hartsuiker, & Pickering, 2007); in more advanced L2 learners, priming is slightly larger without lexical overlap (Bernolet et al., 2013). This suggests that, at least when there is no L1 equivalent of the L2 structure, L2 learners initially rely on lexical-specific knowledge, and only later develop more abstract structures (McDonough, 2006).

Results from previous L2 priming studies therefore suggest that L2-learners, like native speakers, are sensitive to the nature of the immediately preceding language context and can adjust their own language use to this context.

On the other hand, there is evidence that L2 speakers have difficulties using the context to adjust their L2 language representations. For instance, in spite of object (accusative)-initial sentences being not uncommon in German, even advanced English L2 learners of German do not appear to use this information to adjust their parsing preferences (Arnon & Ramscar, 2012; Hopp, 2015).

The question addressed in the present study is therefore to what extent L2 speakers show adaptation, and what the nature of priming and adaptation in L2 speakers is. If similar implicit learning mechanisms are operational in native and L2 speakers, both an error-based learning account, and the model proposed by Reitter et al. (2011) would predict that L2 learners as well as native speakers show stronger immediate priming and cumulative adaptation effects for structures that are infrequent to them. The two groups were expected to differ in the size and direction of the effects depending on differences in their pre-existing biases for the structures used. However, only an error-based account would predict that the speakers in both language groups show surprisal effects, that is, priming effects would be larger when the prime contains a structure that is infrequent given the bias of the lexical items used, in this case, the verb.

The present study

The present study was a web-based, written priming study on PO and DO ditransitives (Kaschak & Borreggine, 2008; Pickering & Branigan, 1998). We tested native American English speakers and Korean L2 learners of English, investigating to what extent L2

learners and native speakers adjust their ditransitive production preferences as a function of (1) the number of structures of a certain type encountered (cumulative adaptation to PO and DO structures); (2) the structure of the immediately preceding item (immediate priming by a PO or DO structure); and (3) the unexpectancy of the preceding prime (prime verb surprisal effects). We selected native American English speakers and Korean L2 learners of English in order to investigate the effects of different initial biases for the ditransitive alternation. American English speakers typically prefer the DO structure (Bock & Griffin, 2000; Jaeger & Snider, 2013; Kaschak, 2007; Kaschak et al., 2011), whereas Korean L2 speakers of English highly prefer the PO structure (S. Kim, 2010; McDonough, 2006; Park, 2007; Shin & Christianson, 2012), even though they are familiar with the DO construction (Hinrichs, 2015; Shin & Christianson, 2009). Both an error-based learning, and base-level learning accounts along the lines of Reitter et al. (Reitter et al., 2011) predict larger immediate priming and cumulative adaptation effects for the PO structure in American English speakers (Bock & Griffin, 2000; Jaeger & Snider, 2013; Kaschak, 2007; Kaschak et al., 2011), and for the DO structure for the Korean L2 speakers of English (S. Kim, 2010; McDonough, 2006; Park, 2007; Shin & Christianson, 2012). Second, error-based learning, but not activation-based accounts, predict that both native and L2 speakers would show effects of prime verb bias (surprisal) but differ in the pattern of surprisal effects depending on differences in verb biases between the groups.

Participants

Seventy-four American English speaking participants completed the questionnaire, mainly recruited from US college communities. Data from two of these participants were not included in the analysis because English was not their native language or they indicated to be much older (71 years) than the remaining participants. We therefore included data from 72 native English participants in the analysis (age 18-52, mean age 23.7). In addition, 75 Korean second language learners of English completed the questionnaire. The participants were recruited mainly from South Korean college communities. Data from four of these participants were omitted from analysis because of early exposure to English (two participants), long immersion in an English speaking environment (one participant), or not residing in a Korean-speaking country (one participant). After omission of trials with primes that were not completed or completed incorrectly for our purposes (i.e., no direct object was completed in a DO frame, no *to*-prepositional phrase was completed in a PO frame, see below), data from an additional ten participants were omitted from analysis since they had fewer than two trials remaining in at least one of the three priming conditions. We therefore included data from 61 native Korean participants in the analysis (age 18-27, mean age 20.8). All resided in South Korea. All except one had started learning English after the age of 7 (range 6-20 years; mean age 9.9). Five had spent less than 1 year, and one had spent 1.5 years, in an English-speaking country. Others did not have any immersion experience. Participants read and checked "agree" on an online written informed consent form before starting the study. The protocol was approved by the University of Florida Institutional Review Board.

Materials

Three verbs were used as target verbs (*show*, *hand*, and *offer*); nine different verbs were used as prime verbs (*award*, *bring*, *give*, *pay*, *pass*, *send*, *sell*, *throw*, and *write*) in the main priming study. Verb norms were obtained on the basis of completion data provided by a separate group of 35 native English speaking participants and 34 non-immersed Korean L2 learners of English, drawn from the same populations as the participants in the main study. The norming study was a picture description task, similar to the priming study, except that the sentence fragments only contained the subject and the verb (*The boy gave*…), and that experimental verb trials were always preceded by an intransitive distractor trial. Participants completed one trial for each of the 12 experimental verbs. Three versions of the norming study were conducted, each version having different pictures. Coding of the responses was similar to that described for the main study. Completion data for the 12 verbs are give in Tables S1-3 in the Supplementary materials. Results from the norming study indicated that the prime verbs varied in their biases, at least, in the native English norming data, with *award, give,* and *pay* preferring the DO construction, and *pass, send, sell,* and *throw* having a preference for the PO construction. As each verb was presented in both PO and DO frames in the main priming study, this variation in prime verb bias was intended in order to investigate surprisal effects. The verbs that were used as target verbs in the priming study were either equibiased according to the native English norms (*show*), or slightly biased towards the PO structure (*hand, offer*). We deliberately selected these verbs as target verbs as opposed to more strongly biased verbs to avoid priming effects being obscured by strong target verb biases (Gries, 2005).

In contrast to previous written completion studies (Kaschak & Borreggine, 2008; Pickering & Branigan, 1998), we used a picture description task rather than isolated sentence fragments to encourage completions with both the theme and the recipient. Forty-five black-and-white line drawings depicting ditransitive events were either newly constructed (24 pictures), or adjusted from other studies (Bock, 1989; Bock & Loebell, 1990; Bock, Loebell, & Morey, 1992): nine drawings were prepared for each of the three target verbs, and two for each of the nine prime verbs. The agent and the recipient in the depicted action were always animate, and the theme was always inanimate. Furthermore, nine pictures depicting intransitive events (e.g., a baby crawling) were prepared for baseline trials. We included an additional 46 pictures as fillers, depicting intransitive or transitive events. Most of the filler pictures were taken from the CRL International Picture-Naming Project (http://crl.ucsd.edu/experiments/ipnp/).

Procedure

The priming study was a written, web-based questionnaire conducted using Qualtrics. After completing the consent form, the participant was instructed to describe the pictures by completing the sentence fragments provided including all characters visible in the picture. One example trial and example answer was provided (*The boy kicked the girl who was kicked by the cat*). Each participant was then presented with 100 trials (27 primes; 27 targets; 46 fillers). Trials were presented one at a time, each on a new screen. Prime trials had sentence fragments that either forced a PO completion (*The nurse gave the medicine…*), a DO completion (*The nurse gave the patient…*), or were intransitive

(e.g. a picture of a girl laughing, with the fragment *The girl* ….). Target trials directly following the prime consisted only of a subject and a verb (*The clown showed…*), see Figure 1. No nouns or verbs were repeated between the prime and the target. The order of the trials was pseudorandomized, such that a target was separated from the next prime by one to three filler trials.

<Insert Figure 1 around here>

Each participant saw each combination of prime verb and target verb twice, but each time in a different priming condition and with different pictures. Three versions of the experiment were created such that a ditransitive picture was associated with one priming condition in one list, and another priming condition in another list. Collapsed over all three versions of the experiment, each of the three target verbs was combined with each of the nine priming verbs in both the PO and the DO priming conditions[1]. Participants were randomly assigned to each of the three lists. After the last trial in the priming study, the participants were asked to answer the questions about their language background.

Scoring

Blank responses and responses consisting of random characters were coded as null responses. Prime and target completions were scored as DO when the indirect object NP (recipient) was followed by the direct object NP (theme); completions were scored as PO when the direct object (theme) NP was followed by a prepositional phrase that started with the preposition *to* and described the recipient. Responses were coded as Transitives if the verb was followed by a direct object (theme) only (*The girl handed a book*). "Other" responses included responses in which the theme was missing (*The woman showed a handsome guy*), or responses with scrambled orders (*The boy handed to singer a guitar; The librarian handed a book a boy*), sentential complements (*The boy showed his mom how well he did on his test),* prepositional phrase being the theme (*The woman offered the man to bag*), the use of *for* rather than *to* (*The woman offered briefcase for husband business*), the use of a different verb than the one provided in the target fragment; and completions that did not fall under any of the above. Responses were classified into the above categories regardless of typographical errors or omission of determiners.

Results and analysis

Target responses

Native English

Out of the 1944 total target responses collected from the 72 native English speakers, 20 were null responses and were omitted from analysis. In addition, 102 primes were not

completed, or were completed incorrectly for our purposes (i.e. no direct object NP was completed in a DO frame, or no prepositional phrase was completed in a PO frame). These trials were also omitted from analysis. The final data set consisted of 1822 responses. Table 1 gives an overview of the response type for each of the priming conditions. The Native English group showed a slight preference for a DO response. Numerically, fewer DO responses were produced after a PO prime than after a DO prime. The native English group produced few Transitive and Other responses, and produced such responses at a roughly equal rate across the priming conditions.

<Insert Table 1 around here>

Korean learners of English

Out of the 1647 total responses collected from the 61 Korean L2 English speakers, we omitted 44 null responses and 213 trials of which the prime was not correctly completed. This yielded 1390 data points for analysis. Table 2 gives an overview of the response type for each of the priming conditions for the Korean L2 English participants. In contrast to the Native English group, the Korean learners of English showed a large preference for a PO response, with hardly any DO responses being produced as target completions. The Korean group also produced more Transitive (e.g., *The man showed a hat*) and Other responses than the native English group. Numerically, more Transitive responses were produced after a DO prime than after a PO or baseline prime. This suggests that the L2 Korean speakers used the Transitive rather than the DO construction as alternating with the PO constructions. Given the small number of DO responses in the

Korean group, and their apparent use of the Transitive as alternating with the PO structure, we chose to conduct analyses on the PO responses relative to the DO and Transitive responses. A reduction in the number of PO responses after a DO prime (versus a baseline prime) can be interpreted as sensitivity to the difference between the PO and DO structure. Restricting the analyses to DO and PO responses only may not have captured the learners' sensitivity to the priming structure. In the Supplementary materials we report an analysis restricted to PO and DO responses only (Tables S7-12). An additional 16 L2 learners were dropped in the latter analysis because they had fewer than two responses in a particular cell. Analyses yielded similar cumulative adaptation effects for the baseline condition as reported in the main text.[2]

<Insert Table 2 around here>

Effects of cumulative adaptation and immediate priming

To investigate to what extent the two groups differed in the effect of cumulative adaptation, we included as factor in our analysis the number of DO constructions and the number of PO constructions completed by the participant prior to the target trial. Previous studies (Jaeger & Snider, 2008; Messenger et al., 2011) distinguished between constructions perceived as primes and constructions produced as targets to assess across-subject and within-subject persistence. However in our study, perception of the prime cannot be easily distinguished from production of the prime, since the participant was

asked to complete the incomplete structure provided by the prime. For this reason, we collapsed across the number of preceding primes and targets, without distinguishing perception from production.

We conducted a logistic linear mixed effects model using R version 3.2 (R Core Team, 2015) on responses to target trials that were immediately preceded by a DO, PO, or baseline prime. The dependent variable was the type of target response, with PO coded as 1 and DO and Transitive coded as 0. The data set analyzed (including DO, PO and Transitive responses only) included 1813 data points for the English participants and 1329 for the L2 participants. Fixed effects in the model were: prime condition (PO, DO, baseline; treatment coded, with baseline primes as the baseline level), language group (Native English, L2; sum-coded), number of prior DO constructions completed by the individual (as prime or target), number of prior PO constructions completed by the individual (as prime or target), the interactions between prime condition and each of the other factors, interactions between language group and each of the other factors, the triple interaction between prime condition, language group and number of prior DO, and the triple interaction between prime condition, language group and number of prior PO. All fixed effects, with the exception of prime condition, were centered around the mean to reduce collinearity and facilitate interpretation of the coefficients. Participant and item (where "item" is each combination of target verb and target picture) were included as random factors. As per Barr, Levy, Scheepers and Tily (2013) we started with a maximum random effect structure. However, due to convergence problems, the random effects only included the random by-subject and by-target item intercepts, by-subjects

and by-items random slopes for prime condition, and by-subject slopes for the number of prior PO and DO constructions, unless noted otherwise.

A table with all results from the analysis is presented in the Supplementary materials (Table S4). Native English speakers produced fewer PO targets than Korean learners of English in the baseline primes (effect of language, β = -1.15, S.E. = 0.43, z = -2.69, p = .01). Of interest to our research question is that language group interacted with the number of prior PO constructions (β = -0.13, S.E. = 0.05, z = -2.82, p = .00). In addition, there were significant or near-significant triple interactions between language group, PO priming (versus baseline), and the number of prior PO (β = 0.12, S.E. = 0.05, z = 2.24, p = .03) or DO trials (β = -0.15, S.E. = 0.08, z = -1.81, p = .07). To further explore these effects, we conducted separate analyses for each language group. Results are in Tables 3 and 4, and will be discussed below.

<Insert Table 3 around here>

<Insert Table 4 around here>

Cumulative adaptation

Both groups showed effects of cumulative adaptation: more PO structures were completed in the baseline condition when more prior PO constructions had been encountered; fewer PO constructions were produced when more DO constructions had been encountered (see the baseline condition in Figures 2 and 3). The native English

speakers showed a stronger adaptation to the number of prior PO structures than the Korean speakers of English, leading to the interaction of Language by the Number of Prior PO structures in the main analysis. For the Native English group (Table 3), the cumulative effect of the number of preceding structures, as indicated by the β coefficient for the number of prior PO and DO structures, was somewhat larger for the PO than the DO structures: for every PO structure encountered, the PO productions increased with 0.35 logits, whereas for every DO encountered the PO productions decreased (that is, the non-PO productions increased) with 0.27 logits. For the Korean learners of English (Table 4), the effect of the number of prior DO structures was larger than that of the number of prior PO structures: for every PO encountered, the PO productions increased with 0.24 logits, whereas with every DO encountered, the PO productions decreased with 0.47 logits. These results suggest that larger cumulative adaptation effects are seen for the structure that is less frequent to the language user, namely the PO structures in the native English speakers, and the DO structures in the Korean learners of English.

<Figure 2 around here>

<Figure 3 around here>

However, we need to be careful interpreting the results for the Korean learners of English. Only 12 of the Korean participants produced DO constructions aside from the forced completions in the 9 DO primes. Hence, only very few data points were available for trials with more than 9 preceding DO constructions. To get a better understanding of the cumulative adjustment related to the number of preceding DO structures, we

conducted another analysis on the Korean L2 data in which we only considered target trials with fewer than 10 preceding DO structures. Results were similar to those reported for the main analysis: the likelihood of a PO production decreased as more DO constructions were encountered (β = -0.81, S.E. = 0.22, z = -3.60, p < .0001), and this effect was larger than the increase in the likelihood of a PO production as more PO constructions had been encountered (β = 0.55, S.E. = 0.16, z = 3.45, p < .0001). Since the DO constructions are less frequent than the PO constructions in Korean L2 English, this pattern was expected.

Immediate priming effects and cumulative adaptation

The Native English speakers showed numerically stronger priming effects for PO primes versus baseline (coefficient (β) 0.32) than for DO primes versus baseline (coefficient 0.05), whereas the Korean L2 English group showed numerically stronger effects of DO primes (coefficient -0.24) than PO primes (coefficient -0.10). Although neither group showed significant effects of priming versus the baseline condition, the coefficients pattern in the expected directions given that the groups started out with different frequencies of the two constructions. Additionally, the groups differed in the modulation of the immediate priming effects by the number of preceding trials. The PO priming effect in the English group was affected by the number of PO constructions encountered in the experiment, leading to a significant interaction of PO prime (vs. baseline) by the number of prior POs. This effect is illustrated in Figure 2, left panel: After having encountered only few PO structures, the native English group produced more PO targets

after a PO prime than after a baseline prime; when more PO constructions had been encountered, more PO targets were produced after a baseline than after a PO prime (reverse priming effect). The number of preceding DO constructions had less of an effect, although numerically *more* PO targets were produced after a DO prime than after a baseline prime with more preceding DO constructions (Figure 2, right panel).

The Korean L2 speakers of English did not show strong effects of the number of preceding DO or PO trials on the size of the priming effect (Figure 3).

Summary: cumulative and immediate priming

To summarize, both the Native English and the Korean L2 English groups showed effects of cumulative adaptation: both showed an increase in the likelihood of producing a PO construction after a baseline prime as more PO constructions had been encountered in the experiment; both showed an increase in the likelihood of producing a non-PO construction (DO or Transitive) after a baseline prime as more DO constructions had been encountered. The Native English group showed a larger adaptation effect for the PO structures than the Korean learners of English. Within each group, the slope of the adaptation effect was steeper for the least frequent structure (PO in the native English group, and DO in the L2 Korean group). These results suggest that both groups have an abstract representation of the PO structure and of the alternate structure, and are sensitive to the frequency with which these constructions are encountered (even though the Korean L2 speakers may collapse the representation of a DO with that of a Transitive, see Discussion).

The groups also differed in the modulation of immediate priming effects by the number of previous constructions seen. The native English group produced more PO targets after a PO prime than after a baseline prime at the beginning of the experiment, but were more likely to produce a PO after a baseline prime when more PO constructions had been encountered, leading to a reverse immediate priming effect. On the other hand, the Korean learners of English produced numerically fewer PO constructions after a DO prime than after a baseline prime, but this was not modulated by the number and type of constructions encountered.

Verb bias and surprisal

To investigate to what extent native English speakers and Korean learners of English were sensitive to the properties of the verbs, we conducted a logistic linear mixed effects model on data restricted to trials containing a DO or PO prime. We omitted trials with a baseline prime because the (intransitive, transitive) verbs in this condition did not have any DO or PO bias. Fixed effects were: prime condition (sum coded, DO vs. PO), language group (sum coded, Native vs. Korean L2), target verb bias, prime verb bias, and the interactions between prime condition and each of the previous factors, and between language group and each of the previous factors, the triple interaction between prime condition, language group and target verb bias, and the triple interaction between prime condition, language group and prime verb bias. The random effects included the by-subject and by-item intercepts (where “item” is the combination of target verb and target picture), and prime condition as a by-subject and by-item random slope. Models with a

more complex random-effect structure did not converge. Target verb bias and Prime verb surprisal were estimated using the English norming data (see methods). Prime verb surprisal was computed as the negative base-2 log of the probability that the verb occurred in the (PO or DO) construction used in the prime, relative to it occurring in the alternate ditransitive or Transitive construction (Jaeger & Snider, 2013). Larger values on this measure correspond to larger surprisal. Target verb bias was estimated using the log odds of the verb occurring in a PO versus DO or Transitive construction. The larger this number, the stronger the PO bias of the verb (Bernolet & Hartsuiker, 2010). Outcomes of the model are given in Table 5. An analysis using verb bias and surprisal measures calculated on the basis of PO and DO responses only yielded similar effects.[3]

< Insert Table 5 around here >

As in the previous analysis, Korean learners of English produced more PO constructions than native English speakers, leading to a significant effect of Language group. There was no effect of surprisal, that is, the bias of the prime verb had no effect on priming (in contrast to Bernolet & Hartsuiker, 2010; Jaeger & Snider, 2008). The bias of the target verb did affect the target production preferences: the stronger the PO bias of the target verb, the more PO responses were produced. Table 6 shows the responses for each of the three target verbs. The verb *showed* yielded fewer PO responses than the other two verbs. This verb had the weakest bias for a PO construction in the norming results (see Supplementary materials, Table S3).

< Insert Table 6 around here >

We had expected the Native English and Korean L2 English groups to differ in prime verb surprisal effects, since the two groups may entertain different verb biases. To further explore differences in prime verb surprisal effects we conducted separate analyses on the Korean and the English group, using the verb bias information collected for these specific groups in the norming study. Results from these analyses are given in the Supplementary materials (Tables S5 and S6). In the Native English group the priming effect was not modulated by prime verb surprisal (β = -0.12 , S.E. = 0.21, z = -0.56, p = 0.58). In the analysis using Korean Verb biases, the Korean learners of English showed a weak effect of prime verb surprisal on priming (β = -1.02 , S.E. = 0.59, z = -1.74, p = 0.08). However, the direction of the effect is different from what is expected on the basis of error-based learning: priming effects become smaller with larger prime verb surprisal, as opposed to becoming larger. The L2 Korean English learners had a PO preference for the prime verbs, hence surprisal was systematically large in the DO prime conditions. The reverse surprisal effect on priming suggests that L2 Korean English learners tended to complete the target as a PO, even when the PO biased prime verb appeared in a DO frame and was associated with large surprisal in this group.[4]

Summary: Verb bias effects

Participants were sensitive to the bias of the target verb: fewer PO targets were produced when the target verb was less strongly biased for PO structure. However, neither group showed effects of surprisal, that is, immediate priming effects did not become stronger when the prime verb occurred in a structure that was less typical for that verb.

Discussion

The aim of this study was to investigate to what extent native and L2 speakers adapt their language use to the preceding context, in particular, as a function of (1) the number of structures of a certain type encountered (cumulative adaptation); (2) the structure of the immediately preceding item (immediate priming); and (3) the unexpectancy of the preceding prime structure given the prime verb bias (prime verb surprisal effects). Under both error-based learning, and base-level learning models such as Reitter et al.'s ACT-R model (Reitter et al., 2011), differences between the native and the L2 group were expected to be due to differences in pre-existing frequencies of the structures and biases between the groups. Immediate priming and cumulative adaptation effects were expected to be stronger for structures that the participants had encountered less frequently in their daily language use. These predictions were borne out: priming and adaptation effects were larger for the PO structures in the Native English speakers, and for the DO structures in the Korean L2 English speakers. However, whereas both groups showed significant cumulative adaptation effects to the number of preceding DO and PO structures, immediate priming effects were not significant in the L2 learners, and only attested at the beginning of the study for the native English group. In addition, under an error-based learning approach, priming effects were expected to be larger when the prime structure is infrequent given the prime verb bias (surprisal). We did not find any surprisal effects, however. We will discuss these findings below.

Cumulative adaptation

Results showed cumulative adaptation in both the native English and L2 groups, for both PO and DO constructions. The native English group adapted significantly more strongly to the PO structures over the course of the study than the Korean L2 English group. In addition, based on the size of the coefficients, the native English group showed a slightly larger effect of the number of preceding PO structures than DO structures, whereas the L2 speakers showed a larger adaptation to the DO than the PO structures. Recall that DO structures are typically somewhat more frequent than PO structures in American English, whereas the PO structure is by far the most frequent ditransitive in Korean L2 English. These results suggest that both native speakers and Korean L2 learners have an abstract structural representation of the two ditransitive structures, whose activation changes as a function of the number of times these structures have been recently encountered. This adaptation is strongest for structures that are initially infrequent. Since L2 and native groups start out with different frequency preferences, the patterns of adaptation are slightly different between the groups. This can be explained by error-based learning: language users initially expect the structure that is most frequent for them. When this expectation is not met, the alternative, less frequent structure gets boosted. The results can also be accounted for by base-level leaning models (Reitter et al., 2011) in which the base-level activation of a structure is increased with each use; infrequent structures benefit more from this boost, resulting in a stronger adaptation effect for the infrequent structures (Hartsuiker, Kolk, & Huiskamp, 1999; Hartsuiker & Westenberg, 2000; Kaschak, 2007; Kaschak et al., 2006).

Immediate priming effects

Also in support of frequency-dependent adaptation, the native English speakers showed an effect of immediate priming for the initially infrequent PO constructions; this effect decreased (or even reversed versus the baseline conditions) as more PO structures had been encountered in the experiment and the participants started to use more PO structures overall (Hartsuiker et al., 1999; Hartsuiker & Westenberg, 2000; Kaschak, 2007; Kaschak et al., 2006). The L2 group showed a numerically stronger effect of immediate priming for the less frequent structure (non-PO structure) than for the more frequent structure (PO).

In contrast to the cumulative adaptation effects, however, the immediate priming effects were much weaker, and even only numerically present in the L2 learners. Especially given the strong preference for the PO structure in the Korean L2 learners, priming effects for the infrequent DO construction were expected to be very strong under both an error-based learning account and a base-level learning account. The discrepancy between the robust cumulative adaptation effects and the weak immediate priming effects, especially in the L2 speakers, can be accounted for in several ways. We will discuss the underspecification of the structure, weaker predictive processing, and task characteristics.

The cumulative adaptation effects suggest that both native speakers and Korean L2 learners of English have an abstract structural representation of the alternate structures, however the absence of immediate DO priming effects in Korean L2 English learners in this and other studies can be taken to suggest that Korean L2 English learners lack an abstract representation of the DO structure (S. Kim, 2010; McDonough, 2006; Park, 2007). This discrepancy between the cumulative and immediate priming effects can

be reconciled by assuming that the Korean L2 English speakers have an underspecified non-PO ditransitive alternate. The Korean L2 English learners in our study often produced a transitive structure as a target (*The clown showed the hat)* instead of a DO (*The clown showed the cowboy the hat)*. Judging from Table 2, more transitives were produced after a DO prime than after a PO prime. The observation that DO ditransitives (cumulatively) primed transitives suggests that the Korean L2 English learners treated the DO and the transitive constructions as similar at some level of representation. Our proposal is that the Korean L2 learners entertain a non-PO ditransitive construction of the form [V (NP_1) NP_2], in which the NP representing the indirect object (NP_1) is optional or not robustly represented. This structure is activated each time the participant encounters a DO or a Transitive in a ditransitive event, leading to cumulative adaptation effects.

Assuming an underspecified non-PO ditransitive structure, the weak immediate DO priming effects in the L2 learners can be accounted for as follows. Under a prediction-based approach to priming (Dell & Chang, 2014), the Korean L2 learners strongly expect a PO construction when processing the prime fragment, since the PO structure is the most frequent to them. In such a structure, the NP following the verb is the (typically inanimate) direct object. Hence, when reading *The boy threw…* the L2 parser expects the next phrase to be *the ball* or another inanimate object. However, in the DO primes in the present study, the verb is followed by an animate, indirect object NP (e.g., *his friend* in *The boy threw his friend…).* This sequence leads to an error signal, since the participant expects a direct object (inanimate noun phrase, e.g., *the ball*) to follow the verb. However, this error cannot be used to immediately boost the structure, since the animate NP cannot be directly mapped onto the underspecified indirect object

NP_1 in the [V (NP_1) NP_2] construction. As a result, immediate priming from the DO prime onto the activation of the non-PO structure is rather weak. Alternatively, one can assume that immediate priming is partly driven by spreading activation, as in the model proposed by Reitter et al. (2011). Since the DO prime structure is underspecified in the Korean L2 learners, the cues provided by the prime do not lead to spreading activation that can strongly boost the target structure. In both models, the non-PO ditransitive structure can increase in activation after the prime trial has been fully processed and completed. This activation may be too weak for a strong immediate priming effect, but does give rise to the cumulative adaptation effect. Obviously more research is needed to work out such accounts in detail.

A second potential reason why immediate priming effects were weak is that the L2 learners may not have actively predicted the elements after the verb in the prime structure. As explained in the above, prediction is necessary to obtain an error signal. Previous research on predictive processing in L2 learners has shown that L2 learners may not predict, or may not always predict in a native-like way (see for an overview, Kaan, 2014). Under error-based views of priming, the learners will not have received an error signal when encountering a DO prime, and hence will not have adjusted their memory representations in response to the prime structure. This may account for the weak immediate priming effect, but does not explain the cumulative priming effects.

A third reason why the Korean L2 learners may not have shown robust priming of the infrequent structure is that the completion task may not have enforced deep processing of the prime structure. In contrast to studies in which the participant is asked to repeat the complete prime, or listens to the complete prime spoken by a confederate,

the completion task used in this experiment presented only partial primes that the participants had to complete with a direct object or prepositional phrase. Furthermore, the task was not timed, and we did not control how long a break participants could take between their completions. Even in native speakers, written completion tasks have yielded rather weak effects of immediate priming (Pickering & Branigan, 1998). Participants' attention may therefore not have been drawn to the priming structure, resulting in only a weak activation of this structure. In addition, we did not repeat the verb between the prime and the target. Priming effects are typically larger with lexical repetition (Cleland & Pickering, 2003; Pickering & Branigan, 1998), especially in low-proficient L2 speakers (Bernolet et al., 2013). The prime-based increase in activation of the infrequent DO prime structure may not have been robust enough to strongly affect the completion of the target, but was strong enough to lead to accumulation of the activation of the DO structure (or its non-PO ditransitive equivalent) resulting in the cumulative adaptation effect.

Verb bias effects

The third prediction that follows from an error-based learning approach, but not from the model prosed by Reitter et al., is that priming effects are stronger if the prime structure used is infrequent given the biases of the verb used in the prime. Such surprisal effects have been attested in previous studies on native speakers (Bernolet & Hartsuiker, 2010; Jaeger & Snider, 2008; Jaeger & Snider, 2013). However, neither the native English speakers, nor the L2 learners showed increased priming effects with larger prime verb

surprisal in the present study. Only the bias of the target verbs had an effect: regardless of the prime condition, participants were more likely to produce a PO construction with the verbs *hand* and *offer*, which were slightly PO biased, than with the equibiased target verb *show* (for effects of target bias, see e.g., Gries, 2005; Peter et al., 2015). The observation that L2-learners are sensitive to subcategorization biases in L2 is supported by a growing number of other studies showing that L2 speakers can use subcategorization information during L2 processing, although the L2 bias may not always be native-like (Dussias, Marful, Gerfen, & Bajo, 2010; Gries & Wulff, 2005; Lee, Lu, & Garnsey, 2013).

The absence of a prime verb surprisal effect in our study, even in our native speakers, was not predicted under an error-based learning approach. However, the absence of prime verb surprisal effects is not unique to this study (see e.g., Peter et al., 2015), and can be attributed to the specific materials or tasks used, or developmental factors. In support of the latter, Peter et al. (2015) reported that the 3 to 4- and 5 to 6-year-old children tested in their priming study showed a much stronger effect of surprisal than adults. Peter et al. (2015) speculate that the learning rate is larger in children than in adults. In children, prediction errors therefore result in more rapid changes with respect to the weights associated with knowledge representations. As the children mature, their learning rate gets smaller. Old knowledge can no longer easily be overwritten by new experiences, leading to stabilization of the learner's knowledge (Chang et al., 2006). The reduced learning rate in adults may explain why the native speakers in our study did not show a surprisal effect. If our results are representative of adult L2 learners, this may suggest that the learning rate is not re-set with the acquisition of a new language, but rather biologically determined. Alternatively, the L2 learners' learning rate may be

smaller because of the presence of their previous (L1) experience, which may then block the acquisition of new alternatives (Arnon & Ramscar, 2012). This issue warrants further investigation. The absence of surprisal effects in the current study, therefore, is compatible with error-based learning approaches as well as models that do not assume error-based learning.

Conclusions and future research

Results from the present study suggest that L2 speakers are similar to native speakers in adapting their language use to the preceding language context. Both show cumulative adaptation effects which are larger for the structure that is initially less frequent to them. Differences between L2 learners and the native speakers can be accounted for by differences in starting frequency and the nature of the structural representation entertained. The current findings support the view that adaptation occurs through implicit learning, be it error-based learning or through other mechanisms that incorporate a frequency-dependent modulation of activation of structures (Reitter et al., 2011).

The observation that adult L2-learners adapt their language use to the surrounding language context has implications for language learning. If adaptation is driven by error-based learning, what kind of input would lead L2-learners to efficiently and quickly adjust their knowledge in the direction of the target language? In order for errors to be informative, L2 learners would need to experience errors (Arnon & Ramscar, 2012), and would need to know what to change, or which structure to boost in response to the errors. We suggested in the above that the Korean L2 learners may experience a prediction error

when reading the animate NP following the verb in the DO primes. However, this error cannot serve as a good cue to boost the DO structure, since the indirect object may be underspecified in the Korean L2 learners' representation of the non-PO ditransitive, and the animate NP cannot be directly mapped into the indirect object slot. An interesting question is then what kind of errors would cue the L2 learners to make the structural representation of the non-PO ditransitive more native-like? Some structures may be tied to some specific lexical items in beginning learners. Learners generalize these constructions to other lexical items as they become more proficient (e.g., Bernolet et al., 2013; McDonough, 2006; Tomasello, 2000). Previous studies report that L2 English speakers use DO structures primarily with pronouns (Hawkins, 1987; McDonough, 2006). In a corpus study on written essays by Korean learners of English (Yonsei English Learners' Corpus, Rhee & Jung, 2014), we also observed that Korean L2 learners of English produce more DO structures with pronouns (75%) than with other noun phrases (25%), whereas PO structures were used more overwhelmingly with other noun phrases (95%) than with pronouns (5%, Hinrichs, 2015). Using priming and adaptation paradigms in which a variety of noun phrases are used may therefore encourage the activation of a more native-English like DO structure. Also, learners with different levels of L2 proficiency are expected to differ in their extent and rate of adaptation. More experience in the L2 may affect the structural representations, and structural and lexical biases, and hence, the ability to use prediction errors to adapt to the preceding language context.

Another question, which we did not investigate in the current study, is to what extent adaptation persists. McDonough (2006) reports immediate priming effects, but no persistence of the DO structure when the L2 learners are tested in a delayed post-test. If

error-based learning and adaptation are considered important mechanisms underlying language learning, it is crucial to investigate what type of paradigms and manipulations yield the strongest persistence.

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Footnotes

1. Due to an coding error, the verb *throw* was presented twice in the DO prime condition for a third of the participants, rather than once in the PO and once in the DO condition.

2. However, due to the limited number of DO responses, the effect of Target verb bias was no longer significant when this analysis was restricted to the Korean L2 data. In the analysis on the native English group, in contrast, the interaction between Target Verb Bias and prime reached significance when the data set was limited to DO and PO responses only.

3. With the exception that the effect of priming was significant in the analysis on all participants when verb biases were based on PO and DO responses only.

4. An analysis on the Korean L2 English group using English verb biases yielded only an effect of Target Verb Bias.

Table 1. *Native English speakers' target completions as a function of prime condition.*

Prime Condition	*PO*	*DO*	*Transitive*	*Other*	*Prop. PO*[*]
PO	261	273	23	2	0.47 (0.49)
DO	248	344	28	3	0.40 (0.42)
Baseline	263	349	24	4	0.41 (0.43)
Total	772	966	75	9	0.42 (0.44)

[*] Proportion of PO completions based on the number of PO, DO and Transitive completions. Number between parentheses is the proportion of PO completions based on the number of PO and DO completions. PO Prepositional object dative; DO double object dative.

Table 2. *Korean L2 English speakers' target completions as a function of prime condition.*

Prime Condition	*PO*	*DO*	*Transitive*	*Other*	*Prop. PO*[*]
PO	246	26	108	16	0.65 (0.90)
DO	252	36	170	14	0.55 (0.88)
Baseline	300	34	157	31	0.61 (0.90)
Total	798	96	435	61	0.60 (0.89)

[*] Proportion of PO completions based on the number of PO, DO and Transitive completions; Number between parentheses is the proportion of PO completions based on the number of PO and DO completions. PO: Prepositional object dative; DO: double object dative.

Table 3. *Results from the logistic mixed-effects model on the PO productions for the Native English participants.*

Fixed Effect	β	*SE*	*z-value*	*p-value*
Baseline prime (Intercept)	-0.60	0.23	-2.64	**.01**
DO Prime vs. baseline	0.05	0.23	0.23	.82
PO Prime vs. baseline	0.32	0.22	1.45	.15
Nr of prior PO (in baseline prime)	0.35	0.04	8.01	**.00**
Nr of prior DO (in baseline prime)	-0.27	0.04	-7.07	**.00**
DO Prime vs. baseline:Nr of prior PO	-0.08	0.04	-1.86	.06
PO Prime vs. baseline:Nr of prior PO	-0.10	0.05	-2.11	**.03**
DO Prime vs. baseline:Nr of prior DO	0.08	0.04	1.83	.07
PO Prime vs. baseline:Nr of prior DO	0.04	0.04	0.89	.37

Based on 1813 data points; Loglik = -801. Interactions are indicated with ":". Random effects include by-subject and by-item intercepts; Prime as a by-subject and by-items random slope, and Number of preceding PO and DO as by-subject random slopes.

Table 4. *Results from the logistic mixed-effects model on the PO productions for the Korean L2 English participants.*

Fixed Effect	β	*SE*	*z-value*	*p-value*
Baseline prime (Intercept)	0.76	0.29	2.61	**.01**
DO Prime vs. Baseline	-0.24	0.24	-1.02	.31
PO Prime vs. Baseline	-0.10	0.28	-0.37	.71
Nr of prior PO (in Baseline primes)	0.24	0.04	5.46	**.00**
Nr of prior DO (in Baseline primes)	-0.47	0.10	-4.64	**.00**
DO Prime vs. Baseline:Nr of prior PO	-0.04	0.04	-1.02	.31
PO Prime vs. Baseline:Nr of prior PO	0.05	0.05	0.92	.36
DO Prime vs. Baseline:Nr of prior DO	-0.02	0.07	-0.29	.77
PO Prime vs. Baseline:Nr of prior DO	-0.17	0.09	-1.81	.07

Based on 1329 datapoints; Loglik = -560.4. Random effects include by-subject and by-item intercepts, Prime as a by-subject and by-items random slope, and Number of preceding PO and DO as by-subject random slopes.

Table 5. *Results from the logistic mixed-effects model on the PO productions as a function of Prime Verb Surprisal and Target Verb Bias for all participants.*

Fixed Effect	β	*SE*	*z-value*	*p-value*
(Intercept)	-0.13	0.20	-0.64	0.52
Language	1.01	0.39	2.57	**0.01**
Prime	0.29	0.15	1.88	**0.06**
Prime Verb Surprisal	-0.09	0.08	-1.17	0.24
Target Verb Bias	2.74	0.68	4.05	**0.00**
Language: Prime	-0.11	0.31	-0.36	0.72
Language: Prime Verb Surprisal	-0.13	0.16	-0.80	0.42
Language: Target Verb Bias	1.55	1.29	1.20	0.23
Prime: Prime Verb Surprisal	-0.24	0.16	-1.44	0.15
Prime: Target Verb Bias	2.13	1.31	1.63	0.10
Language: Prime: Prime Verb Surprisal	-0.33	0.33	-1.01	0.31
Language: Prime: Target Verb Bias	-2.16	2.59	-0.83	0.40

Based on 2015 observations; Loglik = -1027.4. Random effects include by-subject and by-item intercepts, Prime as a by-subject and by-items random slope, and Verb surprisal as by-subject slope.

Table 6. *Native English and L2 English speakers' target completions as a function of target verb, collapsed over DO and PO primes.*

	Native English				*Korean L2 English*			
Target Verb	*PO*	*DO*	*Trans.*	*prPO*	*PO*	*DO*	*Trans.*	*prPO*
hand	181	198	15	0.46	172	21	79	0.63
offer	171	195	16	0.45	174	19	83	0.63
show	157	224	20	0.39	152	22	116	0.52

prPO: Proportion of PO completions based on the number of PO, DO and Transitive (Trans.) completions.

Figure Captions

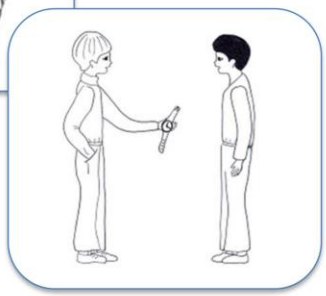
Figure 1. An example of a PO prime-target pair. Prime and target trials were presented on subsequent screens.

Figure 2. Model results for the Native English group: Effects of cumulative adaptation of the number of preceding PO structures (left) and DO structures (right) on the probability of producing a PO target. The number of prior structures (x-axis) is centered; logits converted to probability space (y-axis); error bars are 95% confidence intervals.

Figure 3. Model results for the Korean L2 English group: Effects of cumulative adaptation of the number of preceding PO structures (left) and DO structures (right) on the probability of producing a PO target. The number of prior structures (x-axis) is centered; logits converted to probability space (y-axis); error bars are 95% confidence intervals.

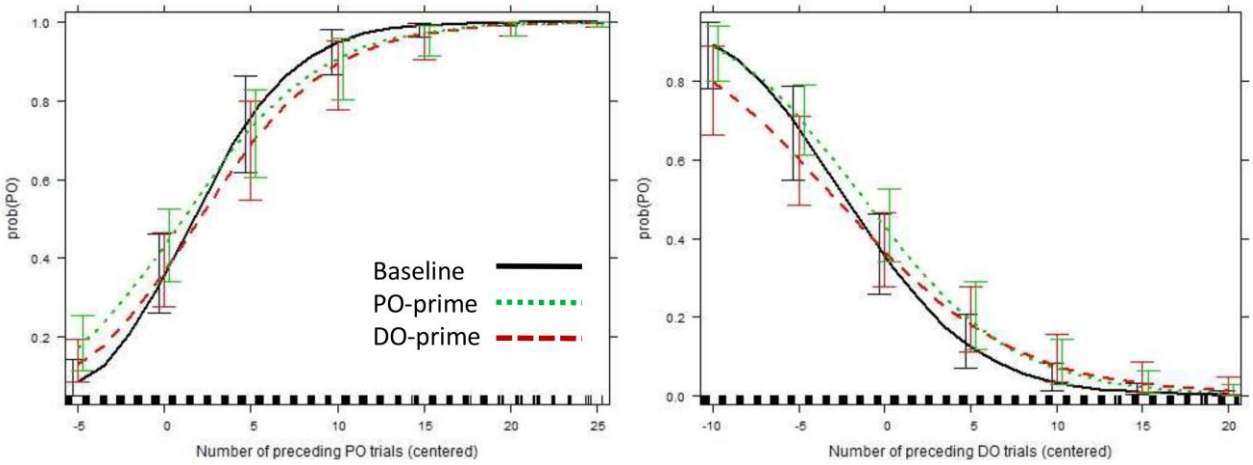
Prime (PO):

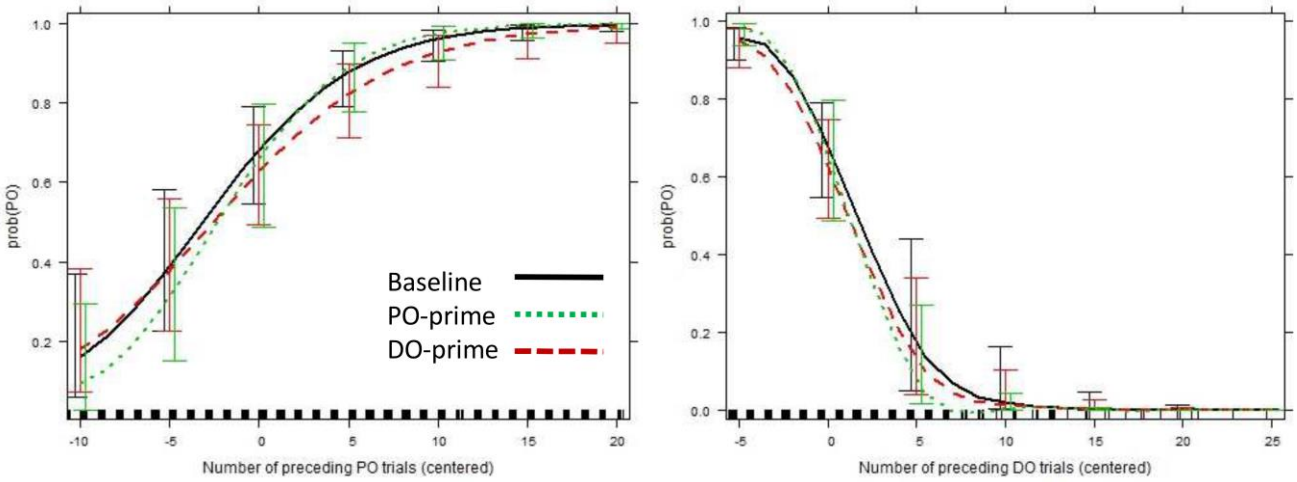
The principal awarded a trophy _____



Target:

The boy showed _____


prob(PO)
Number of preceding PO trials (centered)
Baseline
PO-prime
DO-prime
prob(PO)
Number of preceding DO trials (centered)


prob(PO)
1.0
0.8
0.6
0.4
0.2
-10
-5
0
5
10
15
20
Number of preceding PO trials (centered)
Baseline
PO-prime
DO-prime
prob(PO)
1.0
0.8
0.6
0.4
0.2
0.0
-5
0
5
10
15
20
25
Number of preceding DO trials (centered)

Supplementary Materials

Table S1

Native English Verb Biases

		PO	*DO*	*Transitive*	*Other*	*DO surprisal*[1]	*PO surprisal*
Prime verb	award	6	15	2	12	0.59	1.78
	bring	20	12	2	1	1.43	0.74
	give	14	21	0	0	0.71	1.26
	pass	30	4	0	1	2.81	0.18
	pay	6	16	3	10	0.61	1.89
	sell	23	5	6	0	2.54	0.54
	send	28	7	0	0	2.17	0.31
	throw	24	6	1	4	2.19	0.36
	write	25	1	7	2	4.09	0.39

[1]DO surprisal: -Log2((DO+1)/ (PO+DO+Trans+1)); PO surprisal: -Log2((PO+1)/ (PO+DO+Trans+1))

Table S2

Korean L2 English Verb Biases

		PO	*DO*	*Transitive*	*Other*	*DO surprisal*[1]	*PO surprisal*
Prime verb	award	15	1	3	13	3.32	0.32
	bring	19	2	8	3	3.32	0.59
	give	20	4	4	5	2.54	0.47
	pass	24	1	6	1	4.00	0.36
	pay	16	0	12	5	4.86	0.77
	sell	13	0	16	4	4.91	1.10
	send	28	0	3	2	5.00	0.14
	throw	25	1	5	1	4.00	0.30
	write	17	0	11	5	4.86	0.69

[1]DO surprisal: -Log2((DO+1)/(PO+DO+Trans+1)); PO surprisal: -Log2((PO+1)/(PO+DO+Trans+1))

Table S3

Target verb biases in English and Korean speakers

Bias Group	*Target Verb*	*PO*	*DO*	*Transitive*	*Other*	*Log(PO+1/ DO+1)*	*Log(PO+1/ DO+Trans+1)*
English	hand	22	13	0	0	0.22	0.22
	offer	21	13	1	0	0.20	0.17
	show	17	17	0	1	0.00	0.00
Korean	hand	25	0	7	1	1.41	0.51
	offer	22	1	7	1	1.06	0.41
	show	18	2	10	3	0.80	0.16

Table S4

Results from the logistic mixed-effects model on the PO productions, investigating the effects of immediate priming, cumulative adaptation and language group

Fixed Effect	β	*SE*	*z-value*	*p-value*
Baseline (Intercept)	-0.13	0.21	-0.64	.52
Language (in Baseline)	-1.15	0.43	-2.69	**.01**
DO Prime vs. Baseline	-0.28	0.20	-1.42	.16
PO Prime vs. Baseline	-0.17	0.23	-0.77	.44
Nr of prior PO (in Baseline)	0.30	0.03	9.87	**.00**
Nr of prior DO (in Baseline)	-0.33	0.04	-8.06	**.00**
Language: DO Prime vs. Baseline	0.01	0.39	0.02	.98
Language: PO Prime vs. Baseline	-0.75	0.47	-1.62	.11
Language: Nr of prior PO	-0.13	0.05	-2.82	**.00**
Language: Nr of prior DO	-0.11	0.07	-1.55	.12
DO Prime vs. Baseline: Nr of prior PO	-0.07	0.03	-2.40	**.02**
PO Prime vs. Baseline: Nr of prior PO	-0.04	0.03	-1.22	.22
DO Prime vs. Baseline: Nr of prior DO	0.04	0.04	1.12	.26
PO Prime vs. Baseline: Nr of prior DO	-0.04	0.04	-0.94	.35
Lang: DO Prime vs. Base: Nr of prior PO	0.05	0.05	1.14	.25
Lang: PO Prime vs. Base: Nr of prior PO	0.12	0.05	2.24	**.03**
Lang: DO Prime vs. Base: Nr of prior DO	-0.10	0.07	-1.46	.14

Lang: PO Prime vs. Base:Nr of prior DO	-0.15	0.08	-1.81	.07

Based on 3142 data points; Loglik = -1373; interactions are indicated with ":". Random effects include by-subject and by-item intercepts; Prime as a by-subject and by-items random slope, and Number of preceding PO and DO as by-subject random slopes.

Table S5

Results from the logistic mixed-effects model on the PO productions for the Native English participants investigating the effects of Prime Verb Surprisal and Target Verb Bias

Fixed Effect	β	*SE*	*z-value*	*p-value*
(Intercept)	-0.53	0.26	-2.06	0.04
Prime	0.37	0.21	1.81	0.07
Prime Verb Surprisal	-0.06	0.10	-0.57	0.57
Target Verb Bias	1.48	0.97	1.53	0.13
Prime: Prime Verb Surprisal	-0.12	0.21	-0.56	0.58
Prime: Target Verb Bias	3.01	1.66	1.81	0.07

Based on 1177 data points; Loglik = -623.0. Random effects include by-subject and by-item intercepts; Prime as a by-subject and by-items random slope, and Prime Verb Surprisal and Target Verb Bias as a by-subject random slope.

Table S6

Results from the logistic mixed-effects linear model on the PO productions for the Korean L2 English participants as a function of Korean Verb biases

Fixed Effect	β	*SE*	*z-value*	*p-value*
(Intercept)	-0.25	0.60	-0.42	0.68
Prime	-1.43	1.18	-1.22	0.22
Korean Prime Verb Surprisal	-0.44	0.28	-1.59	0.11
Korean Target Verb Bias	2.51	0.90	2.78	**0.01**
Prime: Korean Prime Verb Surprisal	-1.02	0.59	-1.74	0.08
Prime: Korean Target Verb Bias	0.79	1.38	0.58	0.56

Based on 838 data points; Loglik = -398.0. Random effects include by-subject and by-item intercepts; Prime as a by-subject and by-items random slope, and Korean Prime Verb Surprisal and Korean Target Verb Bias as a by-subject random slope.

Table S7

Analysis on PO and DO responses only. Results from the logistic mixed-effects model on the PO productions (relative to DO productions), investigating the effects of immediate priming, cumulative adaptation and language group.

Fixed Effect	β	*SE*	*z-value*	*p-value*
Baseline (Intercept)	0.79	0.22	3.61	**0.00**
Language	0.66	0.52	1.27	0.20
DO Prime vs. Baseline	-0.17	0.20	-0.87	0.38
PO Prime vs. Baseline	-0.20	0.22	-0.90	0.37
Nr of prior PO (in Baseline)	0.33	0.04	7.68	**0.00**
Nr of prior DO (in Baseline)	-0.35	0.04	-8.10	**0.00**
Language:DO Prime vs. Baseline	-0.16	0.63	-0.26	0.80
Language:PO Prime vs. Baseline	-1.15	0.68	-1.68	0.09
Language:Nr of prior PO	-0.08	0.07	-1.23	0.22
Language:Nr of prior DO	-0.25	0.08	-3.01	**0.00**
DO Prime vs. Base:Nr of prior PO	-0.02	0.04	-0.55	0.58
PO Prime vs. Base:Nr of prior PO	-0.03	0.05	-0.76	0.45
DO Prime vs. Baseline:Nr of prior DO	0.03	0.05	0.56	0.58
PO Prime vs. Baseline:Nr of prior DO	-0.03	0.05	-0.57	0.57
Lang: DO Prime vs. Base:Nr of prior PO	0.12	0.08	1.53	0.13
Lang: PO Prime vs. Base:Nr of prior PO	0.11	0.08	1.34	0.18
Lang: DO Prime vs. Base:Nr of prior DO	-0.08	0.09	-0.88	0.38

Lang: PO Prime vs. Base:Nr of prior DO	-0.12	0.11	-1.04	0.30

Based on 2572 data points; Loglik = -927.8. Random effects include by-subject and by-item random intercepts by-subject random slopes for Prime condition, Number of preceding PO, and Number of preceding DO.

Table S8

Results from the logistic mixed-effects model on the PO productions (vs. DO productions) for the Native English participants.

Fixed Effect	β	*SE*	*z-value*	*p-value*
Baseline (Intercept)	-0.41	0.17	-2.48	**0.01**
DO Prime vs. Baseline	-0.02	0.16	-0.15	0.88
PO Prime vs. Baseline	0.31	0.17	1.87	0.06
Nr of prior PO	0.24	0.03	9.15	**0.00**
Nr of prior DO	-0.19	0.02	-7.93	**0.00**
DO Prime vs. Baseline:Nr of prior PO	-0.09	0.03	-2.97	**0.00**
PO Prime vs. Baseline:Nr of prior PO	-0.08	0.03	-2.37	**0.02**
DO Prime vs. Baseline:Nr of prior DO	0.08	0.03	3.05	**0.00**
PO Prime vs. Baseline:Nr of prior DO	0.03	0.03	1.24	0.22

Based on 1738 data points; Loglik = -816.8. Random effects include by-subject and by-item random intercepts, and by-subject random slopes for Prime condition.

Table S9

Results from the logistic mixed-effects model on the PO productions (vs. DO productions) for the Korean L2 English participants.

Fixed Effect	β	*SE*	*z-value*	*p-value*
Baseline (Intercept)	5.53	1.11	4.98	**0.00**
DO Prime vs. Baseline	-0.03	0.96	-0.03	0.98
PO Prime vs. Baseline	0.08	1.15	0.07	0.94
Nr of prior PO (in Baseline)	0.27	0.14	1.98	**0.05**
Nr of prior DO (in Baseline)	-0.68	0.19	-3.52	**0.00**
DO Prime vs. Baseline:Nr of prior PO	0.15	0.10	1.55	0.12
PO Prime vs. Baseline:Nr of prior PO	0.15	0.12	1.29	0.20
DO Prime vs. Baseline:Nr of prior DO	-0.10	0.11	-0.90	0.37
PO Prime vs. Baseline:Nr of prior DO	-0.22	0.15	-1.48	0.14

Based on 834 data points; Loglik = -144.9. Random effects include by-subject and by-item random intercepts, by-subject random slopes for Prime condition, Number of preceding PO and DO.

Table S10

Results from the logistic mixed-effects model on the PO productions (vs. DO productions) as a function of Prime Verb Surprisal and Target Verb Bias for all participants.

Fixed Effect	β	*SE*	*z-value*	*p-value*
(Intercept)	0.91	0.26	3.51	0.00
Language	4.21	0.61	6.91	**0.00**
Prime	0.15	0.23	0.67	0.50
Prime Verb Surprisal	-0.21	0.12	-1.77	0.08
Target Verb Bias	2.49	1.01	2.46	**0.01**
Language: Prime	-0.66	0.66	-1.00	0.32
Language: Prime Verb Surprisal	-0.41	0.35	-1.19	0.23
Language: Target Verb Bias	3.43	2.89	1.19	0.24
Prime: Prime Verb Surprisal	-0.28	0.23	-1.24	0.21
Prime: Target Verb Bias	0.71	1.64	0.44	0.66
Language: Prime: Prime Verb Surprisal	-0.53	0.56	-0.94	0.35
Language: Prime: Target Verb Bias	-7.26	4.11	-1.77	0.08

Based on 1653 observations; Loglik = -724.9. Random effects included a by-subject and by-item intercept, by-subject random slopes for Prime, Prime Verb Surprisal and Target Verb Bias, and a by-item random slope for Prime.

Table S11

Results from the logistic mixed-effects model on the PO productions for the Native English participants, based on PO and DO responses only, as a function of Prime Verb Surprisal and Target Verb Bias.

Fixed Effect	β	*SE*	*z-value*	*p-value*
(Intercept)	-0.42	0.26	-1.64	0.10
Prime	0.35	0.21	1.65	0.10
Prime Verb Surprisal	-0.08	0.11	-0.75	0.45
Target Verb Bias	1.76	0.94	1.87	0.06
Prime: Prime Verb Surprisal	-0.15	0.24	-0.61	0.54
Prime: Target Verb Bias	3.02	1.68	1.80	0.07

Based on 1126 data points; Loglik = -603.8. Random effects included a by-subject and by-item intercept, by-subject and by-item random slope for Prime, and by-subject random slopes for the interaction of Prime and Prime Verb Surprisal, and the interaction of Prime by Target Verb Bias.

Table S12

Analysis on PO and DO responses only: Effects of Prime Verb Surprisal and Target Verb Bias, Korean participants only, using verb biases obtained from Korean learners of English

Fixed Effect	β	*SE*	*z-value*	*p-value*
(Intercept)	-1.10	5.91	-0.19	0.85
Prime	-16.31	11.88	-1.37	0.17
Prime Verb Surprisal	-4.89	3.34	-1.46	0.14
Target Verb Bias	6.55	4.22	1.55	0.12
Prime: Prime Verb Surprisal	-9.60	6.92	-1.39	0.17
Prime: Target Verb Bias	-0.83	2.62	-0.32	0.75

Based on 527 data points; Loglik =-113.3. Random effects included a by-subject and by-item intercept, by-subject random slopes for Prime, Prime Verb Surprisal and Target Verb Bias, and a by-item random slope for Prime.