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Error-Based Learning: A Mechanism for Linking Verbs to Syntax

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Abstract

Children and adults are guided by verb-specific syntactic likelihoods, or verb bias, in language comprehension and production. Recent reports showed that verb bias can be altered by new linguistic experience. We investigated the mechanisms underlying this verb bias learning or adaptation. Specifically, we asked whether verb bias learning, like abstract syntactic priming, is driven by error-based implicit learning. We report three experiments in which we altered the biases of familiar dative verbs in children's and adults' sentence production, via training trials that induced participants to produce each verb consistently in either double-object or prepositional-object dative structures. Participants' syntactic choices in later test trials reflected the expected adaptation of verb bias to the training experience. In addition, the magnitude of the training effect varied with the likelihood of each sentence structure and with pre-existing verb bias: Unexpected verb-structure combinations resulted in larger training effects, suggesting the operation of error-based implicit learning.

Keywords: language acquisition; verb bias; implicit learning; error-based learning; surprisal

Introduction

Verbs are choosy about the sentence structures they occur in. Transitive but not intransitive verbs can appear in transitive sentences, with two noun-phrase arguments (*She saw Sue*; **She slept Sue*); only certain verbs permit dative structures, with three arguments (*She showed the book to Sue*; **She saw the book to Sue*). In addition to these all-or-none licensing restrictions, the linking of verbs with syntax is constrained by syntactic likelihoods. Most verbs license multiple structures, but may occur much more often in one structure than another. To illustrate, many dative verbs license both the prepositional-object (PO: *He showed/passed the book to her*) and the double-object dative structure (DO: *He showed/passed her the book*), but the verb *show* occurs much more often in the DO structure than does *pass*. These verb-specific likelihoods are known as verb bias. Verb bias knowledge guides language processing in children and in adults, affecting how we link verbs and syntax in production, and online expectations about likely sentence structures in comprehension (e.g., Peter et al., 2015; Snedeker & Trueswell, 2004).

Verb bias effects emerge early in acquisition (Peter et al., 2015; Tomasello, 1992), but continually adapt to ongoing linguistic experience in children and adults. Recent reports show that the biases of even well-known verbs can be altered by

new linguistic experience (Coyle & Kaschak, 2008; Lin & Fisher, 2016; Qi, Yuan & Fisher, 2011; Ryskin, Qi, Duff & Brown-Schmidt, 2016). For instance, Lin and Fisher (2016) asked children and adults to describe videos by repeating and completing sentence stems provided by an experimenter. Training stems (10 per verb) induced participants to produce one verb only in DO structures (*Dora gave Boots* ___), and another verb only in PO structures (*Minnie showed the clock* ___). Test stems ended at the verb, allowing participants to choose either dative structure (*Piglet gave* ___; *The teacher showed* ___). This brief training changed the biases of a wide range of familiar verbs in adults' and 4-year-olds' sentence production. In unconstrained test trials, participants produced more DO descriptions with verbs trained in DO than in PO structures. Similar verb-bias training effects have been found in children's and adults' comprehension of sentences with a prepositional phrase attachment ambiguity (e.g., *Tickle/choose the frog with the feather*; Qi et al., 2011; Ryskin et al., 2016). These findings tell us that learners keep track of the statistics of verb-structure combinations in the linguistic environment, and adapt their language-processing systems accordingly.

In the present study, we explored error-based learning as a potential mechanism for verb bias learning. To do so, we explored parallels between verb bias learning and abstract syntactic priming. Syntactic priming is the tendency to reuse a previously encountered syntactic structure. For example, a talker who has recently read a sentence in the DO structure (*The governess made the princess a pot of tea*) is more likely to choose the same structure to describe an unrelated picture (*The boy is handing the singer a guitar*; Bock, 1986). Syntactic priming is abstract—it spans different verbs, as in the example just given. Syntactic priming can be measured in children and adults, and in comprehension and production (Rowland et al., 2012; Thothathiri & Snedeker, 2008). The priming effects are long-lasting (Bock & Griffin, 2000), suggesting that they reflect long-term learning about abstract syntax. Taken together, the literature on syntactic priming, and recent reports of verb-bias learning, suggest that learners adapt to the statistics both of abstract syntactic structures, and of verb-structure combinations (e.g., Wonnacott, Newport, & Tanenhaus, 2008).

Of particular interest here, syntactic priming shows 'inverse preference' or 'surprisal' effects (e.g., Bernolet & Hartsuiker, 2010; Jaeger & Snider, 2013; Peter et al., 2015).

That is, priming effects are larger if the structure of the prime sentence is unexpected. To illustrate, Bernolet and Hartsuiker (2010), in a study of adult sentence production, reported that (a) DO prime sentences exerted a larger priming effect (relative to baseline) than did prime sentences in the more frequent PO structure, and (b) the magnitude of syntactic priming depended on verb bias: The effect of a DO prime was larger if a PO-biased verb (one that rarely appears in this structure) appeared in the prime sentence. Children show similar effects of verb bias on the magnitude of syntactic priming (Peter et al., 2015). This pattern points to error-based implicit learning as a mechanism for syntactic priming: We expect likely structures, and thus learn more from the unexpected, continuously adapting the language-processing system to a changing linguistic environment (Chang, Dell, & Bock, 2006; Jaeger & Snider, 2013).

Could verb bias learning result from the same error-based learning mechanisms that support syntactic priming? If so, then verb bias training effects should vary with training-sentence surprisal. We tested this prediction by adapting the materials of Lin and Fisher (2016) to vary both training structure (DO- vs. PO-training) and pre-existing verb bias (DO-biased vs. PO-biased verbs).

In three experiments, participants watched videos depicting simple transfer events, and were prompted to describe each one by repeating and completing a sentence stem provided by an experimenter (Fig-1). As before, each participant received training trials that induced them to produce DO structures with one verb (DO-training), and PO structures with a second verb (PO-training). Crucially, one of the restricted verbs was chosen to be already DO-biased (e.g., *show*), while the other was PO-biased (e.g., *pass*). The assignment of verbs to training conditions varied between subjects, resulting in two list conditions: In the with-bias list, both verbs were trained in the structure that matched their pre-existing biases (e.g., PO-training for PO-biased *pass*, DO-training for DO-biased *show*). In the contra-bias list, both verbs were trained in the structure that mismatched their pre-existing biases (PO-training for DO-biased *show*, DO-training for PO-biased *pass*). Following this training, participants received test trials in which the sentence stems to be completed ended at the verb. Participants' structural choices in these unconstrained test trials provided our measure of verb

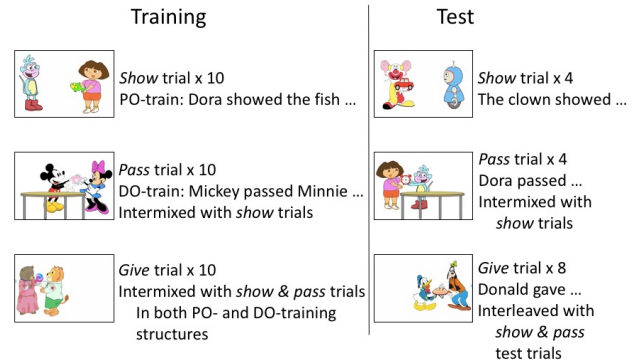


Figure 1. Example of contra-bias training in Experiment 1a.

bias learning.

We work through our predictions for test-trial performance in Fig-2. Each panel shows the expected rate of DO-structure responses (as a proportion of DO and PO responses) under different experimental outcomes, plotted by within-subjects training condition (PO-training vs. DO-training) and between-subjects list condition (with-bias vs. contra-bias).

Based on previous results we expected pre-existing verb bias to affect the rate of DO responses at test. Fig-2a shows the data pattern that would result from baseline verb bias alone: DO responses should be much more common for the DO-biased than for the PO-biased verb. Assuming no training effect, the difference between the two verbs (indicated by the equal-sized arrows in Fig-2a) would not vary with training condition.

We also expected to find a training effect. Fig-2b shows the data pattern that would result if a uniform verb-bias training effect, one that does not vary with training-sentence surprisal, were added to the effect of pre-existing verb bias. As Fig-2b shows, PO-training would decrease the rate of DO responding (relative to baseline), and DO-training would increase the rate of DO responses. Given a uniform training effect, the difference between the two verbs, reflecting pre-existing verb bias, would again remain unchanged.

Fig-2c shows the predicted data pattern if verb bias training effects vary with training-sentence surprisal. Training-sentence surprisal should reflect both the likelihood of the training structure itself, and its fit with the pre-existing bias of the verb. We expected DO-training to exert a larger effect

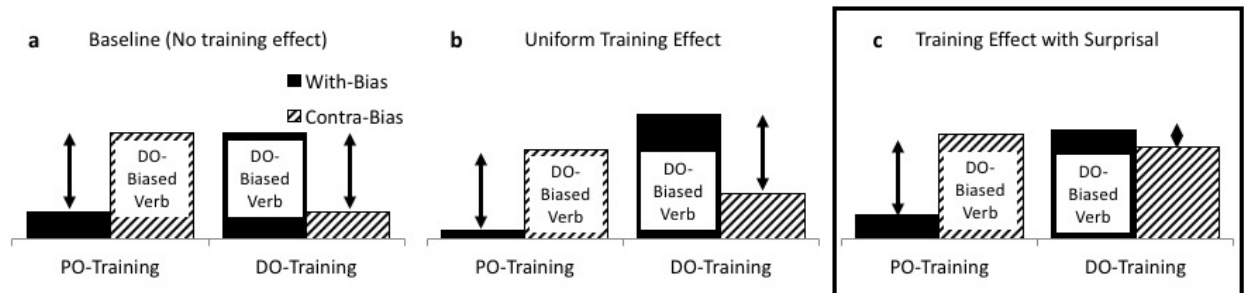


Figure 2. Predicted rate of DO responses, by training condition (PO- vs. DO-training) and list condition (with-bias vs. contra-bias). Fig-2a shows an effect of baseline verb bias only; Fig-2b shows the influence of both pre-existing verb bias and a uniform training effect; Fig-2c shows the key surprisal predictions. In 2c, the rate of DO responses reflects pre-existing verb bias, and an effect of training that is influenced by training-sentence surprisal.

than PO-training, because the DO structure is a non-canonical structure. For example, the DO structure imposes discourse constraints on its use: It is typically used to place discourse-given recipients in post-verbal position (*Show her the picture*; Stephens, 2015). The PO structure, in contrast, has no strong discourse constraints (Brown, Savova, & Gibson, 2008). In our task, without a discourse set-up establishing the recipient as given, the DO structure should be an unexpected choice. We also expected the training effect to vary with pre-existing verb bias: the effect of DO-training should be strongest for PO-biased verbs, those that rarely occur in the DO.

Accordingly, as shown in Fig-2c, DO-training should considerably increase the rate of DO responses for the PO-biased verb (e.g., *pass*), but should have relatively little effect on the rate of DO responses for an already DO-biased verb (e.g., *show*). In the PO-training condition, we should see relatively little change due to training for either verb, preserving the large difference between verbs that reflects their baseline biases. Notice the key difference between Fig-2b and Fig-2c: A training effect that varies with training-sentence surprisal should reduce the difference between the two verbs in the DO-training condition relative to the PO-training condition.

We tested this prediction with 4- and 5-year-olds in Experiments 1a and 1b, and with adults in Experiment 2.

Experiment 1a

Methods

Participants Forty-eight four- and five-year-old children (Mean = 4;8; Range = 4;0-5;11) participated; all were native speakers of English. Data from 4 additional children were excluded due to low training compliance (see below).

Materials and Procedures The materials were 46 5-s animated video clips depicting transfer events designed to be described by dative verbs, and 49 filler videos that did not depict transfer events. Children watched and described all 95 (critical and filler) videos by repeating and completing a sentence stem (Fig-1). The task was adapted from Lin and Fisher (2016), described in the Introduction. The task took about 30 to 40 minutes, and was made engaging for children by embedding it in a scavenger hunt for which game-tokens were discovered at intervals.

The task included a training and a testing block, with no boundary between them from the child's perspective. The key manipulation involved artificially restricting particular verbs to particular dative structures (only DO or PO) in training. As shown in Fig-1, training stems ended with a post-verbal noun, biasing children to produce either a DO or a PO sentence. Test stems ended at the verb. *Show* and *pass* were the two verbs that were restricted in training. These verbs differ in their pre-existing biases, as revealed in a separate norming study. *Show* is used more often in the DO, and *pass* in the PO dative structure. Children were randomly assigned to the with-bias or the contra-bias condition. Recall that in the with-bias condition, both verbs were trained in the structure that matched their pre-existing bias, whereas in the contra-bias

condition, both verbs were trained in the structure that mismatched their pre-existing bias.

A third dative verb, *give*, was unrestricted, appearing equally often in the DO and PO structures during training. Unrestricted *give* (a DO-biased verb) was included to increase children's baseline rate of DO responses in the task; note that children tend to prefer the PO structure in tasks like ours (Peter et al., 2015; Stephens, 2015).

Children received 10 training trials per verb (30 training trials total) in the training block. In the test block children received 4 unconstrained test trials per restricted verb (*show*, *pass*), and 8 test trials for the unrestricted verb *give*. The three verbs were interleaved in training and test, and each child heard equal numbers of DO and PO training stems across verbs, ensuring that any effect of training reflected verb-bias learning rather than abstract syntactic priming.

The main task was preceded by a naming game in which children named the familiar characters and objects involved in the events. The video-description task then began with two filler trials to demonstrate the task.

Children's responses were transcribed and coded as DO, PO, or Other, following Rowland et al.'s (2012) criteria. Children who produced fewer than 80% training-compliant responses in each training condition (e.g., 80% DO responses for their DO-trained verb) were replaced. The 48 included children showed a compliance rate of 94% in training.

Our main analyses concerned the responses in the 8 test trials with experimentally restricted verbs. Of the 384 test responses, 8 were Other responses, leaving 376. The dependent measure was the proportion of DO responses (out of DO and PO responses only), compared across the training and list conditions.

Results and Discussion

Fig-3a shows children's proportion of DO responses in the test trials with restricted verbs, by within-subjects training condition (PO- vs. DO-Training) and between-subjects list condition (with- vs. contra-bias). As predicted, children showed a training effect, producing more DO responses in the DO-training condition (38%) than in the PO-training condition (27%). They also showed a clear effect of pre-existing verb bias, producing more DO responses with the DO-biased verb *show* (43%) than with the PO-biased verb *pass* (22%), averaged across training conditions.

Crucially, the effect of training varied with the likelihood of the training structure and its fit with pre-existing verb bias. Fig-3a shows that DO-training dramatically increased the rate of DO responses for the PO-biased verb *pass*, but had little effect on the rate of DO responses for the already DO-biased verb *show*. This asymmetrical training effect reduced the difference between the two verbs in the DO-training condition relative to the PO-training condition. In the PO-training condition, Fig-3a shows a large difference in the rate of DO responses for the PO-biased verb *pass*, versus the DO-biased verb *show*; this difference straightforwardly reflects

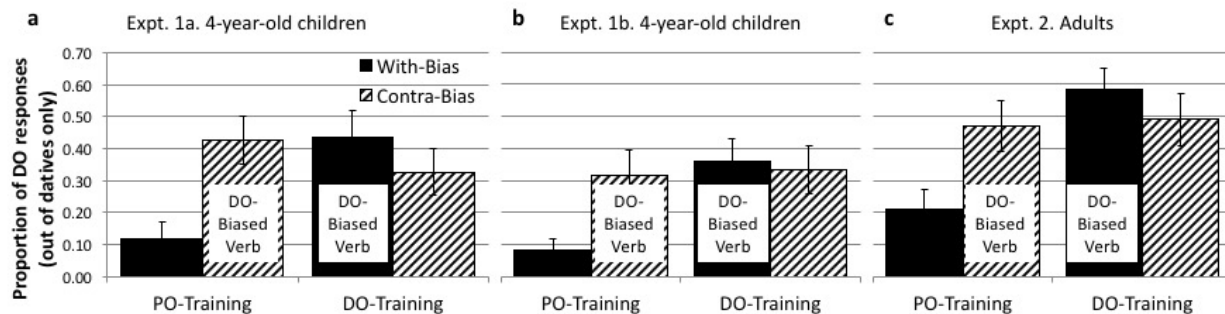


Figure 3. Mean (se) proportion DO responses (out of DO and PO responses) in the test phrase of Experiment 1a (Figure 3a), Experiment 1b (3b) and Experiment 2 (3c), by training condition (PO vs. DO-training) and list (with-bias vs. contra-bias).

the verbs' baseline verb biases. The effect of training was larger for DO- than for PO-training, reflecting the likelihood of each structure; the effect of DO-training was larger for a PO-biased verb, reflecting the likelihood of verb-structure combinations. This pattern of responses closely resembles the predictions shown in Fig-1c, suggesting both an effect of training and an influence of training-sentence surprisal on the magnitude of the training effect.

This pattern was supported by a two-way mixed-model ANOVA on the proportion of DO responses (arcsine transformed) that revealed a main effect of training ($F(1,46) = 5.24, p < .05$), and an interaction of training and list ($F(1,46) = 12.22, p < .01$). Separate t-tests revealed that the difference between the two verbs was significant in the PO-training condition ($t(47) = 3.32, p < .01$) but not in the DO-training condition ($t(47) < 1$), consistent with our surprisal predictions.

In Experiment 1a we reproduced the verb-bias training effect in young children's language production documented in prior work (Lin & Fisher, 2016). Experience producing a verb repeatedly in one syntactic structure modified the structural biases of that verb, rendering children more likely to use the verb in the same structure in later sentences. We also found the first evidence that the magnitude of this training effect depends on the likelihood of the training sentences. In Experiment 1b we sought to extend this effect to different verb sets, exploring the robustness of the surprisal effect.

Experiment 1b

Methods

Participants A new group of forty-eight four- and five-year-old children (Mean = 4;7; Range = 4;0-5;8) participated, all native English speakers. Data from 4 additional children were excluded due to low training compliance (3), or too few dative responses in the test trials (1).

Materials and Procedures Materials and procedures were identical to those of Experiment 1a, except that *send* was the PO-biased verb for half of the children and *throw* for the other half. We chose *send* and *throw*, two other PO-biased verbs, to seek evidence of surprisal effects with different verb sets. We retained *show* as the DO-biased verb to avoid reducing

the verb-bias difference between our restricted verbs in Experiment 1b: Given children's overall preference for the PO structure, our norming study with children identified few strongly DO-biased verbs. As in Experiment 1a, each participant was randomly assigned to the with- or contra-bias list.

Children who produced fewer than 80% training-compliant responses in each training condition were replaced. We also excluded one child who did not produce at least one dative response in the test block for each restricted verb. The included children produced training-compliant responses in 95% of training trials. Of the 384 possible responses in the test trials with restricted verbs, 7 were coded as Other trials, leaving 377 DO and PO responses.

Results and Discussion

Fig-3b shows children's proportion of DO responses in the restricted-verb test trials, by within-subjects training condition (PO- vs. DO-Training) and between-subjects list condition (with- vs. contra-bias). The pattern of responses closely resembles that found in Experiment 1a. Children showed a training effect, producing more DO responses in the DO-training condition (35%) than in the PO-training condition (20%), and an effect of pre-existing verb bias, producing more DO responses for the DO-biased verb *show* (34%) than for the PO-biased verbs (21%).

As before, the effect of training varied with the likelihood of the training structure and its fit with the pre-existing bias. In Fig-3b, DO-training greatly boosted the rate of DO responses for the PO-biased verbs, but had little effect on rate of DO responses for the DO-biased verb *show*. As a result, the difference between the two verbs in the DO-training condition was much smaller than in the PO-training condition. In the PO-training condition, Fig-3b shows a large difference in the rate of DO responses for the PO-biased verbs versus the DO-biased verb, reflecting these verbs' pre-existing verb biases. Therefore, as before, the data bear out our surprisal predictions: the effect of training was larger for DO- than for PO-training, reflecting the likelihood of each structure, and the effect of DO-training was larger for a PO-biased than for a DO-biased verb. The same pattern emerged for both verb sets (not shown in the figure).

These observations were borne out by an ANOVA on the proportion of DO responses (arcsine-transformed) that again

revealed a main effect of training ($F(1,46) = 8.16; p < .01$) and an interaction of training and list ($F(1,46) = 5.83; p < .05$). Separate t-tests revealed that children produced significantly more DO responses for the DO-biased verb *show* than for the PO-biased verbs *send* or *throw* in PO-training ($t(47) = 2.7, p < .01$) but not in DO-training ($t(47) < 1$).

Experiment 1b thus reproduced the key findings of Experiment 1a, varying the verb sets. Again, the pattern of results suggested that the magnitude of verb-bias training depended on training-sentence surprisal. In Experiment 2 we sought evidence of the same surprisal effect in adults, again varying the verb sets.

Experiment 2

Methods

Participants Forty-eight college-aged adults participated, all native English speakers. Data from 2 additional adults were excluded due to low training compliance (1), or too few dative responses in the test block (1).

Materials and Procedures Materials and procedures were identical to those of Experiment 1a, except that *send* and *hand* were the restricted verbs for half of the participants and *pass* and *show* were the restricted verbs for the other half. *Send* and *pass* were both PO-biased verbs in our norming data; *hand* and *show* were both DO-biased. As in Experiment 1a, each participant was randomly assigned to either the with-bias or the contra-bias list condition.

Adults who produced fewer than 80% training-compliant responses in each training condition were replaced. We also excluded one adult who did not produce at least one dative response in the test block for each restricted verb. The included participants produced training-compliant responses in 99% of training trials. Of the 384 possible responses in the test trials with restricted verbs, 8 were coded as Other responses, leaving 376 DO and PO responses.

Results and Discussion

Fig-3c shows adults' proportion of DO responses in the restricted-verb test trials, by within-subjects training condition (PO- vs. DO-Training) and between-subjects list (with- vs. contra-bias). Adults, like children, showed an effect of training, producing more DO responses in the DO-training condition (54%) than in the PO-training condition (34%). They also showed effects of pre-existing verb bias, producing more DO responses with the DO-biased verbs (53%) than with the PO-biased verbs (35%), averaged across training conditions.

The pattern of data shown in Fig-3c again suggests that the effect of training varied with the likelihood of the training structure and its fit with the pre-existing verb bias. The difference between the (pre-experimentally) PO- vs. DO-biased verbs was reduced in the DO-training condition relative to the PO-training condition. This is just what we would predict based on training-sentence surprisal: DO-training strongly increased the rate of DO responding for the PO-biased verbs.

As in Experiment 1b, the same pattern emerged for both verb sets (not shown in the figure).

This pattern was supported by an ANOVA on the proportion of DO responses (arcsine transformed) that revealed a main effect of training ($F(1,46) = 16.73, p < .001$) and an interaction of training and list ($F(1,46) = 12.92, p < .01$). Separate t-tests revealed that the difference between the two verbs was significant in the PO-training condition ($t(47) = 2.35, p < .05$) but not in the DO-training condition ($t(47) < 1$), consistent with the surprisal predictions.

General Discussion

In three experiments, we found that children and adults produced more double-object (DO) sentences for verbs trained in the DO structure than for verbs trained in the PO structure. This difference between training conditions replicates previous reports that the biases of familiar verbs can be altered by new verb-structure patterns in the input (Coyle & Kaschak, 2008; Lin & Fisher, 2016).

We also found the first evidence that the magnitude of the verb-bias training effect depended on the prior likelihood of the training sentences. The key result was that, as predicted, DO-training reduced the difference in DO responses between pre-experimentally DO- and PO-biased verbs. After DO-training, a familiar PO-biased verb such as *pass* became almost as likely to be used in the DO structure as a familiar DO-biased verb such as *show*. In contrast, after PO-training, DO-biased verbs were still used much more often in the DO structure than were PO-biased verbs. This pattern supports the hypothesis that training-sentence surprisal affects verb-bias learning. PO-training, which linked verbs with what is arguably the default dative structure, produced little change in the rate of DO responses relative to the verbs' pre-existing biases; DO-training, which linked verbs with a less canonical structure, led to sizable increases in the rate of DO responses, but did so mostly for PO-biased verbs, reducing the difference between the PO- and DO-biased verbs. This pattern was observed with 4-year-olds (Experiments 1a and 1b) and with adults (Experiment 2).

These findings highlight a strong parallel between verb bias learning and syntactic priming. Prior evidence shows that the magnitude of syntactic priming depends on prime sentence surprisal: The largest priming effects are found when the prime structure is uncommon, or is unexpected given the verb in the prime sentence (Bernoulet & Hartsuiker, 2010; Jaeger & Snider, 2013; Peter et al., 2015). Here we saw strikingly similar effects for verb-bias learning. In both syntactic priming and verb-bias learning, children and adults learn more from unexpected sentences. This similarity suggests that syntactic priming, which involves learning about abstract syntactic structure, and verb bias learning, which involves linking verbs to syntax, depend on similar learning mechanisms and representations.

This conjecture fits well with the predictions of Chang, Dell and Bock's (2006) Dual-Path model of syntax learning. The model learns to link syntax and semantics without pre-defined syntactic representations, in a system that yokes a

syntactic sequencing system to a separate message system representing the meaning of input sentences. A key feature of the model is that the syntactic sequencing system is linked to abstract event-role slots in the message system, but not to the word-meanings bound to those event roles. This “Dual-Path” architecture keeps lexical semantics out of the syntax, ensuring that the model creates abstract syntactic representations. Accordingly, the model creates syntactic representations that support abstract syntactic priming, but the model can also learn about the syntactic biases of particular verbs under some circumstances (Chang, Janciauskas, & Fitz, 2012). Because the model learns via error-based learning, it learns the most from input sentences that are unexpected given the model’s prior experience. This model therefore provides one possible account of our findings—sentence surprisal affects verb bias learning as well as syntactic priming because the same error-based implicit learning mechanism underlies learning about abstract syntax and verb bias.

Our results leave open many questions for future research about the nature of the representations that were modified by verb-bias training. For example, participants could have strengthened the link between each verb and an abstract representation of sentence structure or between a verb and a thematic role ordering (Twomey, Chang, & Ambridge, 2016). Training could have also highlighted the semantic difference between caused possession and caused motion, changing the prominence of recipient vs. theme. Note, though, that adapting the syntax and meanings of verbs are not mutually exclusive (Gleitman et al., 2005).

The verb bias learning studies reported here shed new light on a fundamental question in language acquisition: How do we coordinate abstract syntactic knowledge with our intricate knowledge of words? Our results suggest error-based implicit learning mechanisms help us track the likelihood of both abstract syntactic structures and the linking of those structures with particular verbs. The same learning mechanisms may underlie learning at both levels, creating both abstract and verb-specific syntactic knowledge throughout development.

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