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Verb Biases Are Shaped Through Lifelong Learning

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Verbs often participate in more than 1 syntactic structure, but individual verbs can be biased in terms of whether they are used more often with 1 structure or the other. For instance, in a sentence such as "Bop the bunny with the flower," the phrase "with the flower" is more likely to indicate an instrument with which to "bop," rather than which "bunny" to bop. Conversely, in a sentence such as "Choose the cow with the flower," the phrase "with the flower" is more likely to indicate which "cow" to choose. An open question is where these biases come from and whether they continue to be shaped in adulthood in a way that has lasting consequences for real-time processing of language. In Experiment 1 we replicated previous findings that these language-wide biases guide online syntactic processing in a computer-based visual-world paradigm. In Experiment 2, we tested the malleability of these biases by exposing adults to initially unbiased verbs situated in unambiguous contexts that led to either instrument or modifier interpretations. During test, participants interpreted sentences containing either modifier- or instrument-trained verbs in ambiguous contexts. Eye-movement and action data show that participants' considerations of the candidate interpretations of the ambiguous with-phrases were guided by the newly learned verb biases. These results suggest that co-occurrence information about specific verbs and syntactic structures embedded in language experiences plays a role in forming, and continuously shaping, the verb biases that constitute a part of the broader representation of the language.

Keywords: verb bias, learning, eye-tracking

When interpreting the meaning of a sentence, listeners must identify the underlying syntactic structure. This process is made more complex by the fact that knowing the verb does not fully constrain the syntactic analysis—verbs can participate in multiple structures. For example, the verb *regret* can be followed by either a direct object (e.g., *The senator regretted the decision immediately.*) or a sentential complement (e.g., *The senator regretted the decision had been made public.*). In some cases, the verb's "flexibility" can render the meaning of a sentence temporarily or even globally ambiguous. For instance, without guidance from context, it is unclear whether "*Feel the frog with the feather.*" is referring to a frog that is holding a feather or whether the feather should be used to feel the frog. The ambiguity hinges on the fact that the prepositional phrase "with the flower" can either attach to the verb *Feel* (instrument interpretation), or to the noun *frog* (modifier interpretation). The sentence can take on very different meanings depending on how the ambiguity is resolved.

During language comprehension, accomplishing this feat is facilitated by the fact that multiple cues can be brought to bear on the process of analyzing the syntax of a sentence, including visual information (e.g., if the frog isn't holding a feather in the display), the prior linguistic context (e.g., if the feather has been mentioned as a tool before), and lexical biases. It has been well established in the psycholinguistic literature that particular verbs bias language users' preference regarding how to assign syntactic roles to the upcoming words (Boland, 1997; Boland, Tanenhaus, Garnsey, & Carlson, 1995; Garnsey, Pearlmutter, Myers, & Lotocky, 1997; MacDonald, Pearlmutter, & Seidenberg, 1994; Snedeker & Trueswell, 2004; Spivey & Tanenhaus, 1998; Spivey-Knowlton & Sedivy, 1995; Spivey-Knowlton, Trueswell, & Tanenhaus, 1993;

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Taraban & McClelland, 1988; Trueswell, 1996; Trueswell, Tanenhaus, & Kello, 1993). For instance, when determining the syntactic attachment of an ambiguous *with* prepositional phrase, the verb *choose* is biased toward an upcoming noun-attached modifier in a sentence like *Choose the frog with the feather*, whereas *feed* is biased toward an upcoming verb-attached instrument in a sentence like *Feed the frog with the feather*. Thus, verb bias, the likelihood of the co-occurrence of a particular verb and each syntactic alternative that can be associated with it, provides a strong cue to the intended meaning during sentence comprehension.

The goal of the present research is to examine how these biases in the language come about and whether they are malleable in adulthood. Similar questions about the origins and development of lexical biases have been previously raised in the language acquisition literature (Qi, Yuan, & Fisher, 2011; Snedeker & Trueswell, 2004). The semantic properties of a verb likely play a large role in determining its bias. However, for this to be the only factor that determines a verb's bias, it would have to be the case that word learning entirely precedes the acquisition of syntax. Contrary to this, there is evidence that verb acquisition entails learning the distribution of syntactic contexts in which a verb occurs (Fisher, 1996; Fisher, Gleitman, & Gleitman, 1991; Gleitman, 1990; Naigles, 1990; Snedeker & Gleitman, 2004; see Fisher, Gertner, Scott, & Yuan, 2010 for a review). Thus, in children, the development of lexical biases is likely linked to the syntactic learning process. We hypothesize that there is a role for such learning mechanisms beyond childhood as well. A listener's lexical bias for a given verb may be partly the result of the syntactic constructions that the verb has co-occurred with most often in the listener's experience, with ongoing updates to these representations throughout the life span.

It is well documented that listeners' syntactic analyses are affected by their recent linguistic experiences. Building on findings of syntactic priming in production (Bock, 1986), many studies have found that comprehending a sentence with a particular syntactic structure facilitates subsequent processing of that same structure (Arai et al., 2007; Branigan, Pickering, & McLean, 2005; Kim, Carbary, & Tanenhaus, 2014; Traxler, 2008; for a review, see Tooley & Traxler, 2010). Further, listeners anticipate sentence continuations consistent with a syntactic structure that they have recently heard (Thothathiri & Snedeker, 2008). In addition, repeated exposure to an infrequent structure has been shown to reduce the processing disadvantage associated with parsing unexpected syntactic forms (Bernolet & Hartsuiker, 2010; Fine & Florian Jaeger, 2013; Fine, Jaeger, Farmer, & Qian, 2013; Wells, Christiansen, Race, Acheson, & MacDonald, 2009). Conversely, frequent syntactic structures may become more difficult to process if they are rendered unexpected in the context of the experiment (Fine et al., 2013). In other words, listeners seem to adapt their linguistic expectations to the general distribution of syntactic alternations in the local environment. However, it is unknown at what granularity this environment should be defined or what constitutes an environment or context in our mental representation. If listeners can learn the relative distributions of two structures in the context of an experimental session, can they also learn the relative distributions that are paired with a specific verb? Can the syntactic adaptation be verb-specific?

Syntactic priming in language comprehension has primarily been observed when prime sentences and test sentences have the same verbs, typically in situations where the prime sentence is immediately followed by the target sentence (Tooley, Swaab, Boudewyn, Zirnstein, & Traxler, 2014; Tooley, Traxler, & Swaab, 2009). In an eye-tracking study of reading, Tooley et al. (2014, Experiment 3) show that the facilitatory effect of the prime on reading times persists across lags of up to three intervening sentences, even when the competing syntactic structure is experienced during that lag. In this study, participants read reduced relative clause prime sentences followed by three intervening sentences (a main clause sentence with the same verb as the prime, plus two unrelated filler sentences) and finally a reduced relative target sentence with the same verb as the prime. Evidence for facilitation was obtained by comparing processing times for the target and prime sentences. This result provided the first evidence that syntactic priming in comprehension can persist across linguistic experiences containing competing structures, lending support to the proposal that priming may result from implicit learning mechanisms (Chang, Dell, & Bock, 2006). On this account, listeners' experience with a reduced relative clause strengthens the representation of the reduced relative clause structure—potentially in conjunction with strengthening the connection between the verb and the structure—and thereby leads to reduced processing cost of future reduced relative clause structures. Such an interpretation raises interesting questions about how implicit learning mechanisms may play a role in shaping which structures and verb-structure conjunctions are strengthened in a listener's representation. In the current work, we aim to extend Tooley et al.'s findings using a different paradigm and test whether adults can learn multiple, novel verb-structure bindings from exposure to co-occurrences of lexical items and syntactic structures, and use them to guide online processing.

The Present Research

To answer this question, we examine situations where listeners are presented with sentences that are globally ambiguous, that is, the entire sentence supports two potential, yet contradictory syntactic interpretations. Using a combination of online eye-tracking measures of comprehension and offline measures of the behavioral response to the sentence, we evaluate whether the listeners' interpretation of a specific verb-argument structure is influenced by the syntactic structures that a *particular verb* has been used in.

We first replicate previous findings (Snedeker & Trueswell, 2004) that adults rely on lexical biases when interpreting syntactically ambiguous sentences and show that these findings extend to computer-based stimuli as well as real-world stimuli. In a second experiment, we provide participants with repeated exposure to sets of—initially equibiased—verbs that are exclusively tied to one of two possible syntactic structures (either instrument or modifier-interpreted *with* phrases). Crucially, participants are exposed to both structures with equal frequency throughout the experiment and the syntactic alternations are randomly intermingled (any short-term priming of a structure will be negated by the next exposure to the other alternation).

The results from Experiment 2 provide novel insights into the potential lifelong evolution of listeners' verb biases and extend what has previously been reported in the literature in several important ways. First, Tooley et al. tested a one-directional bias—that is, whether experience with a low-frequency structure leads to a reduction in processing cost that lasts over time. They did this by increasing experience with a single structure and examining the long-lasting influence of this experience on processing that structure. In Experiment 2, we take a different approach, asking if listeners can learn opposing biases for a set of eight verbs in a single session. Participants experience verb-structure co-occurrences, guiding interpretation of one set of verbs toward one syntactic structure and another set of verbs toward a different structure. A positive finding would go beyond the results reported by Tooley et al. that showed an influence of recent experience with a low-frequency structure across delays, and would show that language users can learn from local statistics that some verbs take on one syntactic bias, and other verbs take the opposite bias.

Second, our results address a possible alternative interpretation of the findings in Experiments 2 and 3 of Tooley et al., which provided evidence for syntactic priming across three intervening sentences. In those studies, the critical test of priming came from a comparison of reading times between test sentences and prime sentences. Analyses of eye-gaze during reading revealed that sentences were read faster than prime sentences even with a lag of three intervening sentences. However, the studies lacked a control condition in which the prime sentence was not presented before the test sentence. While supplemental analyses showed no significant effect of serial position across the entire study, it is possible that the passage of time in the study contributed to the observed priming effects (e.g., faster reading times as the study progressed). The present study (Experiment 2) uses a different design where we compare test trials for verbs that have been paired with one syntactic structure to those paired with the other structure. Thus, lag between training and test trials is balanced across training conditions, allowing us to test for an effect of training type without a confounding influence of lag.

In this research, we ask if adult learners continue to shape representations of verbs as they encounter new instances of these verbs and use this information to guide online processing. We do this in a paradigm that allows us to test whether listeners learn from previous experiences with a specific verb, and maintain this information across lags (median lag: six trials) during which the competing syntactic structure is experienced (with other verbs). We use a design where serial position in the experiment is controlled, and the learning occurs in the context of a global ambiguity, where a successful response requires the selection of a syntactic structure. The presence of this choice allows us to draw straightforward conclusions about what associations between verbs and structure have been learned, as the alternative syntactic interpretations are predicted to elicit looks to different objects. In this way, the use of global ambiguity in our design further extends prior results from studies that made use of sentences with temporary ambiguity.

If adults only track overall probability of a given syntactic structure or the representations of verbs are not malleable, we should observe no influence of these verb-structure bindings on real-time processing and interpretation. By contrast, if adults keep track of verb-structure co-occurrences, and use this information to guide ambiguity resolution, we should find that listeners interpret verb-argument structures in a manner isomorphic to the recent experience with that particular verb. Selection of the appropriate structure for a given verb (i.e., the structure that is paired with that verb in the experiment) will be the result of adapting that verb's representation to include a new syntactic bias.

Norming Study

Before Experiment 1, a norming study was conducted to identify the structural preferences of verbs in sentences containing an ambiguous *with* phrase, that is the likelihood of instrument interpretation (as opposed to modifier interpretation) of the prepositional *with* phrase in a frame like VERB the NOUN1 with the NOUN2 (e.g., *Feel the frog with the feather.*).

We selected 37 candidate verbs, including those from Snedeker and Trueswell (2004), based on the requirement that they could be acted out with a computer mouse (e.g., *blow on* was not included because it was hard to imagine how to act that out using the mouse). Each of the 37 verbs was placed in a sentence fragment such as "*He will find the dolphin with the* . . .", along with 20 fillers with a different structure such as "*He will make the squirrel* . . .". Four experimental lists were created; across lists, each of the 37 target verbs was paired with a different noun (e.g., dolphin, frog, etc.). In total, 100 self-reported native English-speaking participants were recruited through Amazon's Mechanical Turk interface, and were paid 75 cents to complete the study, which took less than 15 min. On each trial, participants were given a sentence fragment and were asked to provide a sensible completion to the sentence. Each participant completed the items on a single list.

For each of the 37 target verbs, responses were coded as an instrument continuation (e.g., *He will find the dolphin with the sonar machine.*), with a modifier continuation (e.g., *He will find the dolphin with the missing fin.*), or neither (either unclear or not relevant to the ambiguity). A set of 27 verbs that varied in the degree to which they were used with a modifier versus instrument continuation were selected for the main study (see Appendix A for list of verbs and their bias based on the norming study).

Experiment 1

This experiment was modeled after Snedeker and Trueswell (2004) using a computer-based methodology. The goal was to test for a verb bias effect with adult participants to set the stage for our investigation of the malleability of these effects in Experiment 2.

Method

Participants. Participants were 24 undergraduates at the University of Illinois at Urbana-Champaign, who received partial course credit in return for their participation. All participants were native speakers of English and had normal or corrected-to-normal vision and hearing.

Design and procedure. Participants were instructed to sit in front of a display with pictures of animals and objects and listen to prerecorded speech. Their eye-movements were monitored using an Eyelink-1000 desktop-mounted eye-tracker sampling at 1000 Hz. Stimulus presentation was controlled using Matlab's Psychophysics Toolbox 3 (Brainard, 1997; Kleiner et al., 2007; Pelli, 1997). On every trial, participants first heard a list of all the objects on the screen (e.g., "Here's a duck, a hat, another hat, a sponge, a bird, a sponge."). Every display contained a target animal (e.g., a duck wearing a minihat) and a distractor animal (e.g., a bird holding a minisponge), both with a small inanimate object alongside them, as well as a target instrument (e.g., a hat) and a distractor instrument (e.g., a sponge), which were large versions of those inanimate objects (see Figure 1). Participants then heard an instruction, such as “Pet the duck with the hat.” The animals were always of different types, so that there was always only one possible candidate in the display for the target noun. Unlike Snedeker and Trueswell (2004) we did not manipulate whether there was 1 versus 2 candidate animals in the scene, because this referential context manipulation was not our primary concern.

For each instruction, participants were asked to act out the content of the instruction by clicking on the relevant objects and animals. Critically, the instruction in the context is globally ambiguous and the *with-* phrase could be given an instrument interpretation or a modifier interpretation. For example, to act out an instrument interpretation, a participant might pick up (click and drag) the picture of the hat and drag it over to the duck and motion the hat over the duck. To act out a modifier interpretation, the participant might simply motion the mouse over the picture of the duck that has the hat. Participants’ eye movements were recorded from when the instruction started to when they proceeded to the next trial. The study session consisted of 81 trials and lasted approximately 30 min.

The 81 trials consisted of three practice trials (always the first three trials of the experiment), 24 filler trials, and 54 critical trials. On critical trials, participants heard instructions ending in an ambiguous *with* prepositional phrase. One-third of the critical sentences (18 trials) contained modifier-biased verbs (e.g., cuddle, hug), another third contained instrument-biased verbs (e.g., hit, poke), and the last third contained equibiased verbs (e.g., feel, locate). On filler trials, neither a modifier, nor an instrument interpretation was plausible (e.g., “Make the animals wrestle.”). Filler and critical trials were intermixed and ordered randomly for each participant.

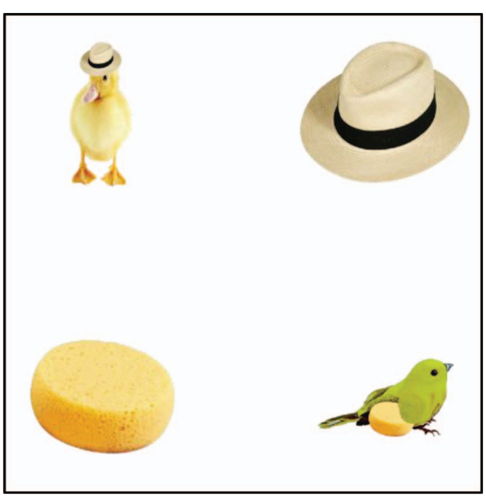

Figure 1. Experiment 1: Example screen during a critical trial (modeled after Snedeker & Trueswell, 2004) corresponding to the sentence “*Pet the duck with the hat.*” The duck wearing the hat is the target animal. The hat is the target instrument. The bird with the sponge is the competitor animal. The sponge is the competitor instrument. See the online article for the color version of this figure.

Materials. The verbs for critical trials were grouped into three categories based on whether they were modifier-biased (9 verbs), instrument-biased (9 verbs), or equibiased (9 verbs); see Appendix A for full list. Each verb was presented twice, each time with a different animal and a different instrument/modifier. The visual stimuli were colorized images (mostly photos and some drawings) selected to provide the clearest possible depiction of each referent. Two lists were made with different pairings of verbs (e.g., pet) with the animals and instruments (e.g., *duck*—hat or *duck-sponge*). Participants were randomly assigned to one of these two lists to ensure that effects were not the result of idiosyncratic properties of animal and instrument images used.

Predictions

Note that the previous study by Snedeker and Trueswell (2004) used real-world objects that participants used to act out the instructions. By contrast the present experiment used a computer display and actions were executed using the computer mouse. Thus one goal of Experiment 1 was to demonstrate the feasibility of examining verb interpretation in an act-out task when all actions were executed with a computer mouse.

We predicted that if we were able to replicate Snedeker and Trueswell (2004), participants would make more fixations to the target animal (e.g., the duck) when the instruction contained a modifier-biased verb than when the verb was instrument-biased or equibiased. We would also see more fixations to the target animal when the verb was equibiased than when it was instrument-biased. We expected to see the reverse pattern for fixations to the target instrument (e.g., the hat). We also predicted a consistent pattern in participants’ mouse-clicking behavior. Participants should be more likely to first click on the target instrument in the instrument-biased condition, and less likely to first click on the target instrument in the modifier-biased condition. Their actions in the equibiased condition should fall in between the other two categories.

Results

Eye-movements. The plot of fixations over time (see Figure 2) is consistent with Snedeker and Trueswell’s pattern of results. We analyzed the data in three time windows to capture eye-movements elicited during both early and later portions of the sentence. All time windows were offset by 200 ms to account for the time needed to program and launch an eye movement (Hallett, 1986). The first time window started at the onset of the verb (e.g., *Pet* in *Pet the duck with the hat*) and ended at the onset of the first noun (e.g., duck). The average duration of the first time window was 732 ms. The second time window began at the onset of the first noun and ended at the onset of the second noun (e.g., hat). The average duration of the second time window was 994 ms. The third time window started at the onset of the second noun and ended 1,500 ms later (the maximum duration of an instrument was 1,421 ms).

For each time window, we analyzed the relationship between eye fixations and the verb bias condition using mixed-effects linear regression. Following Snedeker and Trueswell (2004), we examined fixations to the target animal and the target instrument separately. The dependent variable for these analyses was either the proportion of fixations to the target or the proportion of fixations

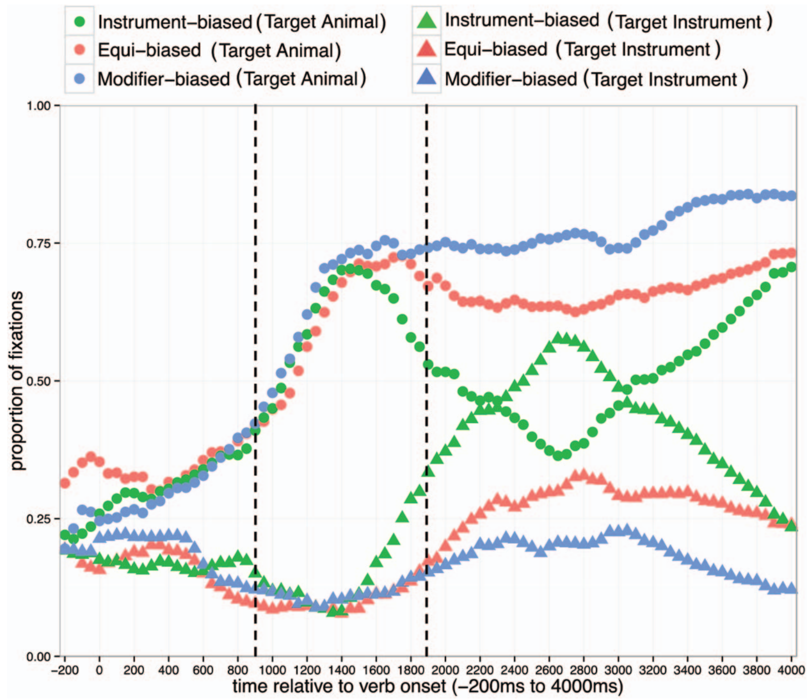

Figure 2. Experiment 1: Proportion of fixations to the target animal and the target instrument across the three verb bias conditions (Instrument-biased, Equibiased, and Modifier-biased) over time in milliseconds. Zero milliseconds corresponds to the onset of the verb (e.g., *Pet the duck with the hat*). Data are aligned at verb onset; dashed lines indicate approximate onsets of Noun 1 and Noun 2, offset by 200 ms. See the online article for the color version of this figure.

to the target instrument. Models included random intercepts for participants and items, as well as random by-participant slopes for verb bias condition (this was the maximal random effect structure justified by the design). Verb bias condition was entered as a pair of orthogonal contrast codes (Cohen, Cohen, West, & Aiken, 2003). The first contrast compared the instrument-biased condition (−2/3) to the average of the equibiased (1/3) and modifier-biased (1/3) conditions. The second contrast compared the equibiased (−1/2) condition to the modifier-biased (1/2) condition. The fixed-effect parameters from these models are summarized in Table 1.

In the first time window (*Pet* . . .), there were no differences across the verb types in fixations to either the target animal or the target instrument. In the second time window (*duck* . . .), participants fixated on the target animal more ($t = 2.34$) and the target instrument less ($t = -2.42$) in the equibiased and modifier-biased conditions compared with the instrument-biased condition. The equibiased and modifier-biased conditions were not significantly different during the second time window. In the third time window (*hat* . . .), participants fixated on the target animal more ($t = 5.22$) and the target instrument less ($t = -5.24$) in the equibiased and modifier-biased conditions compared with the instrument-biased condition. Participants also fixated on the target animal more ($t = 2.06$) and the target instrument less ($t = -1.68$) in the modifier-biased condition compared with the equibiased condition.[1]

Actions. As a measure of participants' behavior, we recorded which object in the display they clicked on first. Participants clicked on the target instrument first on 72% of trials in the instrument-biased condition, 42% of trials in the equibiased condition, and 27% of trials in the modifier-biased condition (Figure 3a). Clicking behavior was analyzed using mixed-effects logistic regression. The dependent measure was whether the first click was on the target instrument or not. The model included random intercepts for participants and items, as well as random by-participant slopes for verb bias condition. Verb bias condition was entered as a pair of orthogonal contrasts, in the same way as in the eye-movement analyses. Participants clicked on the target instrument less ($b = -2.85$, $SE = 0.46$, $t = -6.24$, $p = 4.5e^{-10}$) in the equibiased and modifier-biased conditions compared with the instrument-biased condition. Participants also clicked on the target instrument less ($b = -1.25$, $SE = 0.63$, $t = -1.99$, $p = .05$) in the modifier-biased condition compared with the equibiased condition.

Summary

These findings replicate Snedeker and Trueswell (2004) with a computerized version of the task, illustrating the critical role of verb bias information in online ambiguity resolution. The fact that the verb bias effect began to emerge early in the sentence, during

[1] A complementary analysis with the reverse coding scheme (Instrument-biased: 1/3, Equibiased: 1/3, Modifier-biased: −2/3; Instrument-biased: 1/2, Equibiased: −1/2, Modifier-biased: 0) indicates that the Instrument-biased condition differs significantly from the Equibiased condition in the third time window (target animal looks: $b = -0.20$, $SE = 0.05$, $t = -3.78$, $p < .001$; target instrument looks: $b = 0.20$, $SE = 0.05$, $t = 4.05$, $p < .001$).

Table 1
Experiment 1: Fixed Effects in Multilevel Regression Models for Three Time Windows (Separate Models for Proportions of Fixations to the Target Animal and Proportions of Fixations to the Target Instrument)

	Target animal				Target instrument			
Fixed effects	b	*SE*	*t*	*p*	b	*SE*	*t*	*p*
First time window								
Instrument vs. Equi and Modifier	−.02	.03	−.57	.57	.00	.02	.11	.90
Equi vs. Modifier	−.03	.03	−.98	.32	.02	.02	1.00	.31
Second time window								
Instrument vs. Equi and Modifier	.06	.03	2.34	.02*	−.05	.02	−2.42	.02*
Equi vs. Modifier	.03	.03	1.06	.29	−.02	.02	−.71	.47
Third time window								
Instrument vs. Equi and Modifier	.26	.05	5.22	2e–6*	−.24	.05	−5.24	1.9e–6*
Equi vs. Modifier	.11	.05	2.06	.04*	−.08	.05	−11.68	.097†

† $p < .10$. * $p < .05$.

processing of the animal name but before the second noun, suggests that these biases play a role throughout the processing of the utterance, and not at a delayed or second stage. In summary, the results of this study show that verb-specific structural preferences guide interpretation of global syntactic ambiguities during online sentence processing.

Experiment 2

The goal of the second experiment was to test whether verb biases of existing verbs are malleable. Adults were exposed to familiar equibiased verbs selected from Experiment 1 in unambiguous contexts that led to either the modifier or the instrument interpretation of the *with* prepositional phrases. We asked whether this experience of processing the verbs in unambiguous contexts would guide subsequent interpretation of the same verbs in ambiguous contexts, crucially, in a verb-specific manner.

Method

Participants. Sixty undergraduates at the University of Illinois at Urbana-Champaign participated in the study, in exchange for partial course credit. All participants were native speakers of English and had normal or corrected-to-normal vision and hearing.

Design and procedure. As in Experiment 1, participants listened to prerecorded speech while looking at a display with pictures of animals and objects. They then used the computer mouse to act-out the actions being described in the audio instructions. In contrast to Experiment 1, critical trials were divided into two types: unambiguous training and ambiguous testing trials, which were pseudorandomly intermixed.

On training trials, the audio and visual stimuli were designed to lead to an unambiguous interpretation of the syntactic structure. More important, the large inanimate objects were different from the small objects alongside the target and distractor animals (Figure 4a). On *Instrument Training* trials, participants first heard an unambiguous Instrument setup sentence, such as, "Hmm, what should you use to rub the bunny?" Then they heard the critical instruction, for example, "I know! You should rub the bunny with the bottle." The visual display was designed to elicit an instrument interpretation; it contained a bottle and a bunny that were in separate quadrants, and two other unrelated items.

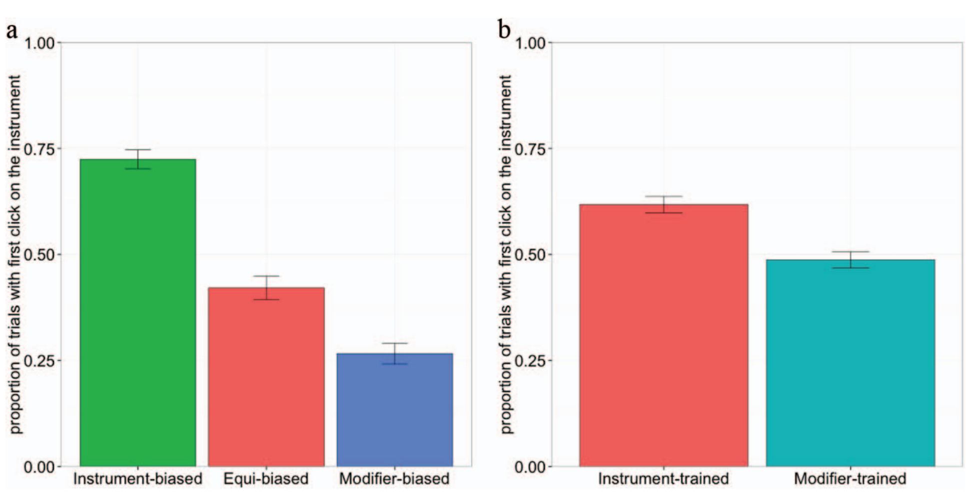

Figure 3. Action data for (a) Experiment 1 and (b) Experiment 2. Error bars represent within-subject *SEM*. See the online article for the color version of this figure.

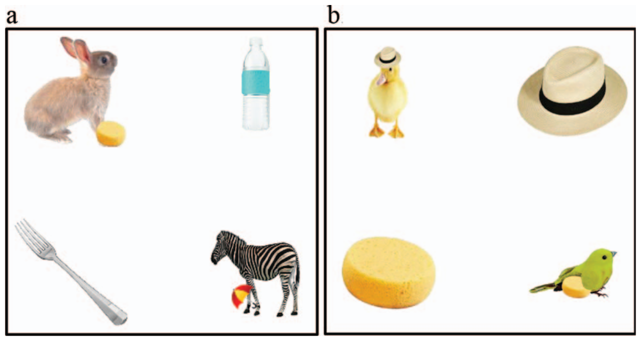

Figure 4. Experiment 2: Displays for training and test trials. (a) For an Instrument training trial, this display would be paired with an instruction such as "I know! You should rub the bunny with the bottle." For a Modifier training trial, the same display would be paired with an instruction such as "I know! You should rub the bunny with the sponge." (b) Ambiguous test trials paired with an instruction such as "I know! You should rub the duck with the hat." See the online article for the color version of this figure.

On *Modifier Training trials*, participants first heard an unambiguous Modifier setup sentence, such as, "Hmm, what animal should you rub?" Then they heard the critical instruction, for example, "I know! You should rub the bunny with the sponge." The visual display contained a bunny attached to a sponge and three other unrelated items, and was designed to elicit a modifier interpretation. Note that a given verb, like "rub," either appeared in the Instrument Training condition or the Modifier Training condition (the pairing between individual verbs and condition was counterbalanced across subjects).

On *Test trials*, the audio and visual stimuli were globally ambiguous with respect to which interpretation should be used. Participants first heard an ambiguous setup sentence, "Hmm, what should you do now?" Then participants heard the critical instruction, for example, "I know! You should rub the duck with the hat." The setup of the visual displays was identical to those of Experiment 1, where the small version of the target instrument is attached to the target animal and the large version is presented in a separate quadrant (Figure 4b). Thus, the visual display did not bias the listeners toward either instrument or modifier interpretation. In the test trials, the verbs were paired with entirely new animals and objects that had not been shown in the training trials.

The testing session lasted 90 min and each participant experienced 163 trials: three practice trials at the beginning, and then 64 filler trials intermixed with 96 critical trials (64 training and 32 test). Each participant was trained on eight initially equibiased verbs; four were Instrument-trained and four were Modifier-trained. Each participant completed four blocks (each block contained four of the critical verbs—two Modifier-trained and two Instrument-trained), arranged such that all eight verbs were presented in each half of the experiment. Each block had 4 unambiguous training trials per verb, and 2 ambiguous test trials per verb, for a total of 24 critical trials per block, intermixed with 16 filler trials. The order of trials within a block was randomized for each participant. The lag between a training trial for a given verb and the next test trial for that verb was, on average, 13 trials (Median = 6, SD = 17). Two lists were constructed to counterbalance verb-training pairings (e.g., for half of the subjects "rub" was Instrument-trained and for the other half it was Modifier-trained) as well as the pairings of verbs with sets of animals and objects. Participants were randomly assigned to one of these two lists.

Filler trials varied in their format, but always included verbs that were not used on critical trials and never contained a modifier-instrument ambiguity. One-third of fillers involved an animal interacting with an instrument (e.g., "What should the elephant smell? I know! Have the elephant smell the flower."). One-third involved just an animal (e.g., "Which animal should go in a circle? Drag the squirrel in a circle."). The last third of filler trials were meant to be very different from the critical trials and involved instruments interacting with instruments (e.g., "Hmm, what should you do now? Put the lollipop beside the straw."), instruments alone (e.g., "What should you do now? Wave the flag."), or animals interacting with animals (e.g., "What should you do now? Make the squirrel kiss the hippo.").

Materials. The eight critical equibiased verbs were selected on the basis of the data patterns for individual verbs in Experiment 1. We selected the eight verbs that elicited comparable consideration of both the modifier interpretation and the instrument interpretation based on fixations to the target instrument, and mouse clicks on the target instrument (see Appendix B for list of verbs). As in Experiment 1, the visual displays contained an animal or an instrument in each of the four quadrants of the scene. Pictures (mostly photographs and some drawings) were selected to provide the clearest possible depiction of each object.

Predictions

If participants can encode bindings of specific verbs with specific (and competing) syntactic structures, and then use this newly learned information during online sentence processing, they should make more fixations to the target animal when the sentence contained a modifier-trained verb as opposed to an instrument-trained verb. Conversely, participants should make more fixations to the target instrument when the sentence contained an instrument-trained verb as opposed to a modifier-trained verb. We also predicted a consistent pattern in participants' mouse-clicking behavior. Participants should be more likely to first click on the target instrument for the instrument-trained condition, and less likely to first click on the target instrument for the modifier-trained condition.

By contrast, participants may be unable to learn and then use a new verb-structure binding in the brief context of the experiment. After all, consider that syntactic priming in comprehension can be lexically independent (Thothathiri & Snedeker, 2008), and our training stimuli expose participants to an equal number of instrument-attach and modifier-attach sentences. If participants accumulate the overall probability of these structures, and do not learn the specific verb-structure bindings, we would expect an equal number of fixations to the target instrument (and target animal) in the modifier-trained and instrument-trained conditions. Along the same lines, because instrument and modifier structures are equally likely overall in the experiment, if participants ignore which verb each structure occurs with, we would predict that participants would be equally likely to click first on the target instrument for the instrument-trained and modifier-trained conditions.

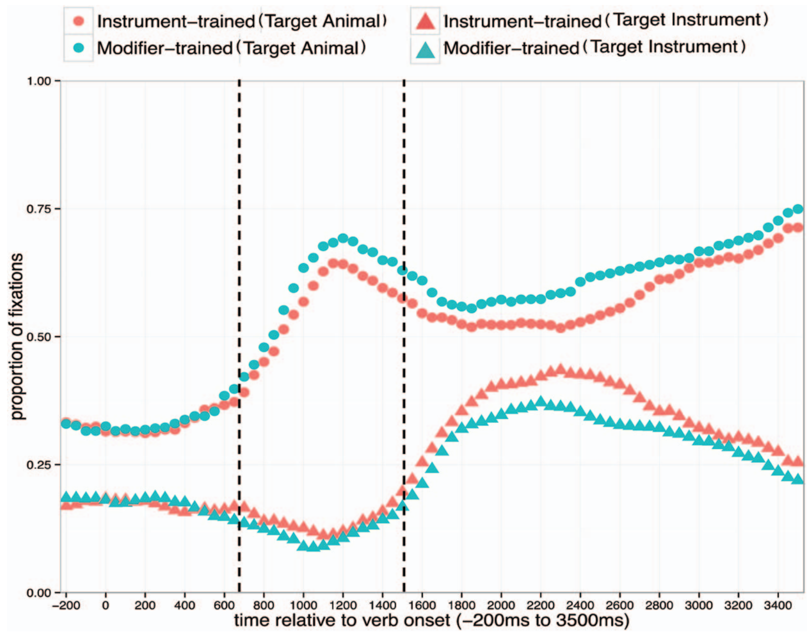

Figure 5. Experiment 2: Proportion of fixations to the target animal and the target instrument across the two training conditions (Instrument and Modifier) over time in milliseconds. Zero milliseconds corresponds to the onset of the verb (e.g., *Rub the duck with the hat*). The data are aligned at verb onset; dashed lines indicate approximate onsets of Noun 1 and Noun 2, offset by 200 ms. See the online article for the color version of this figure.

Results

Eye-movements. The plot of fixations over time (see Figure 5) suggests that participants learned associations between verbs and syntactic attachments. We analyzed the data in the same three time windows as in Experiment 1. The first time window started at the onset of the verb (e.g., *rub*) and ended at the onset of the first noun (e.g., *duck*). The average duration of the first time window was 462 ms.[2] The second time window began at the onset of the first noun and ended at the onset of the second noun (e.g., *hat*). The average duration of the second time window was 843 ms. The third time window started at the onset of the second noun and ended 1,500 ms later.

For each time window, we analyzed the effect of training on the proportion of fixations to either the target animal or the target instrument using mixed-effects linear regression. Random intercepts for participants and items were included, as well as random by-participant and by-item slopes for training condition (the maximal random effects structure justified by the design). Training condition was entered as a deviation coded contrast: Instrument training condition (−1/2) versus Modifier training condition (1/2). The fixed effect parameters from these models are summarized in Table 2.

In the first time window (*rub . . .*), there were no differences in fixations to either the target animal or the target instrument based on training condition. In the second time window (*duck . . .*), participants fixated on the target animal more in the Modifier-trained condition than the Instrument-trained condition ($t = 2.17$). Participants also made numerically, but not significantly, fewer fixations to the target instrument in the Modifier-trained than Instrument-trained condition ($t = -1.30$). In the third time window (*hat . . .*), participants fixated on the target animal more ($t = 2.86$) and the target instrument less ($t = -2.82$) in the Modifier-trained condition as compared with the Instrument-trained condition.[3]

In a post hoc analysis, we examined the durability of this training effect in the third time-window by excluding any test trials that were immediately preceded by a training trial for the same verb (9.5% of the test trials were excluded). The results within this subset mirrored those of the full set of trials. In the third time window (*hat . . .*), participants fixated on the target animal more (b = 0.04, $SE = 0.02$, $t = 2.10$, $p < .05$) and the target instrument less (b = −0.04, $SE = 0.02$, $t = -2.22$, $p < .05$) in the Modifier-trained condition as compared with the Instrument-trained condition.

These findings show that participants learned about verb-specific syntactic distributional information within the context of the experiment. How quickly did listeners adapt to this new distributional information? To address this question, post hoc analy-

[2] The first two time windows in Experiment 2 are shorter in duration than their analogs in Experiment 1. This is likely because stimuli for the two experiments were recorded by different speakers (both male). The critical sentences in Experiment 2 were also embedded within a preamble, for example, "*I know . . .*", which increased the speech rate of the critical sentence itself.

[3] Because of randomization, 9.8% of trials were preceded by zero training trials. These trials were left in in the main analyses because they only work against the effect of interest. When they are excluded the same patterns hold as in the full dataset, in the third time window (target animal looks: b = 0.05, $SE = 0.02$, $t = 2.89$, $p < .01$; target instrument looks: b = −0.05, $SE = 0.02$, $t = -3.17$, $p < .005$).

Table 2
Experiment 2: Fixed Effects in Multilevel Regression Models for Three Time Windows (Separate Models for Proportions of Fixations to the Target Animal and Proportions of Fixations to the Target Instrument)

	Target animal				Target instrument			
Fixed effects	b	*SE*	*t*	*p*	b	*SE*	*t*	*p*
First time window								
Instrument vs. Modifier	.009	.03	.32	.75	−.01	.02	−.87	.39
Second time window								
Instrument vs. Modifier	.04	.02	2.17	.03*	−.02	.01	−1.30	.20
Third time window								
Instrument vs. Modifier	.05	.02	2.82	.006*	−.05	.02	−2.80	.006*

* $p < .05$.

ses examined whether the condition effect evolved over time. An exploratory analysis of looks in the third time window included condition and half of the experiment (first vs. second) as deviation coded factors, along with their interaction. The random effects structure included random intercepts for participants and items, by-item slopes for conditions, and by-participant slopes for condition and half. The analysis of target animal looks revealed a significant main effect of training condition (b = 0.05, $SE = 0.02$, $t = 2.80$, $p < .01$) and a significant main effect of half (b = 0.09, $SE = 0.02$, $t = 3.83$, $p < .0005$), such that proportions of fixations on the target animal were higher in the second half of the experiment. The interaction was not significant (b = 0.01, $SE = 0.03$, $t = 0.47$, $p = .64$). The analysis of target instrument looks revealed an analogous pattern. There was a significant main effect of training condition (b = −0.05, $SE = 0.02$, $t = -2.78$, $p < .01$) and a significant main effect of half (b = −0.09, $SE = 0.02$, $t = -4.12$, $p < .0001$), such that proportions of fixations on the target instrument were lower in the second half of the experiment. The interaction was not significant (b = −0.03, $SE = 0.03$, $t = -0.94$, $p = .35$). When each half is tested separately, the effects are marginally significant in the first half (target animal looks: b = 0.04, $SE = 0.02$, $t = 1.98$, $p = .05$; target instrument looks: b = −0.04, $SE = 0.02$, $t = -1.73$, $p = .08$) and significant in the second half (target animal: b = 0.06, $SE = 0.03$, $t = 2.34$, $p < .05$; target instrument: b = −0.06, $SE = 0.02$, $t = -2.73$, $p < .01$). These results indicate that the training effects began to emerge in the first half of the experiment.

Because training and testing trials were completely randomized within blocks, test trials were preceded by uneven numbers of training trials. As a result, there is not a sufficient number of measurement opportunities at each trial order to provide a powerful test of when significant learning effects emerged within the first block.[4] A different experimental design, with more dense measurement of the effects at each trial order position would likely be required to answer this question.

Actions. As in Experiment 1, we recorded which object participants clicked on first. Participants clicked first on the target instrument on 62% of trials in the Instrument-trained condition and on 49% of trials in the Modifier-trained condition (Figure 3b). Clicking behavior was analyzed using mixed-effects logistic regression. The dependent measure was whether the first click was on the target instrument or not. Random intercepts for participants and items were included, as well as random by-participant and by-item slopes for training condition. Training condition was entered as a deviation coded contrast. Participants made fewer clicks on the target instrument in the Modifier-trained condition compared with the Instrument-trained condition (b = −0.77, $SE = 0.14$, $t = -5.43$, $p = 5.5e^{-8}$).

When each half of the experiment is tested separately, the effects are significant in both the first half (target animal looks: b = 0.57, $SE = 0.21$, $t = 2.64$, $p < .01$; target instrument looks: b = −0.77, $SE = 0.22$, $t = -3.51$, $p < .001$) and the second half (target animal: b = 0.86, $SE = 0.21$, $t = 4.11$, $p < .001$; target instrument: b = −0.83, $SE = 0.20$, $t = -4.11$, $p < .001$). Though the effects appear to be larger in the second half of the experiment, the interaction between training condition and half is not significant (target animal: b = 0.17, $SE = 0.23$, $t = 0.73$, $p = .47$; target instrument: b = −0.04, $SE = 0.23$, $t = -0.16$, $p = .87$) and there is a main effect of half, such that participants click more often on the target animal (b = 0.54, $SE = 0.28$, $t = 1.96$, $p < .05$) and less on the target instrument (b = −0.69, $SE = 0.26$, $t = -2.69$, $p < .01$) as the experiment unfolds.

Summary

Our results provide clear evidence that exposure to the combinatorial information that emerged from the co-occurrence of individual verbs and syntactic structures successfully reshaped learners' syntactic representations of familiar verbs. Participants were more likely to consider a modifier interpretation of a prepositional phrase attachment ambiguity when previous experience with the verb required a modifier interpretation. Conversely, participants were more likely to consider an instrument interpretation when previous experience with the verb tied it to an instrument interpretation. Like the effects of verb bias in Experiment 1, the effect of training emerged early in the sentence—before the onset of the second noun. These findings suggest that adults' verb biases can dynamically adapt as a result of language experience. The newly learned verb biases not only contributed to the final sentence interpretation (as evidenced by the action data), but also the online processing of the sentence itself.

General Discussion

The results of two experiments provide strong evidence for a role of language experience in the lifelong shaping of verb-specific syntactic attachment biases. The results of our first experiment replicated an earlier finding that adults are sensitive to language-wide verb biases (Snedeker & Trueswell, 2004), in a new com-

[4] In an additional post hoc analysis, we looked at the first four test trials in each of the first two blocks (early test) and the last four test trials in each of the last two blocks (late test) for each subject. In the early test trials, we found that the condition effect was absent for proportions of looks to the target animal (b = 0.04, $SE = 0.03$, $t = 1.46$, $p = .14$) and the target instrument (b = −0.04, $SE = 0.03$, $t = -1.53$, $p = .13$). In the late test trials, we found that the condition effect was present for proportions of looks to the target animal (b = 0.07, $SE = 0.03$, $t = 2.29$, $p < .05$) and the target instrument (b = −0.08, $SE = 0.03$, $t = -3.17$, $p < .005$). This suggests that these are not effects that were present from the very first training trials, but they emerge and become quite robust by the end of the experiment.

puterized version of the original task. We found that listeners' online interpretation, as well as offline actions, followed language-wide tendencies (as estimated in a norming task) for the likelihood of a specific verb to be followed by an instrument *with* prepositional phrase, as opposed to a modifier *with* prepositional phrase. In our second experiment, we report the novel finding that adult listeners can flexibly update verb biases of familiar verbs by learning the co-occurrence of syntactic structures and specific verbs in a new linguistic environment. As they processed these familiar verbs, listeners' online consideration of instrument versus modifier interpretations of ambiguous *with* phrases depended on whether the tested verb was previously heard in contexts supporting instrument or modifier interpretation. Newly acquired verb-to-structure mappings were used during online sentence comprehension, guiding online processing. These data suggest that adults' structural preferences for familiar verbs are highly adaptive to newly encountered combinatorial information.

From Syntactic Priming to Verb Bias Learning

It is well established that adult speakers' structural preferences for roughly meaning-equivalent alternations adapt in response to recent input (e.g., Bock, 1986; Bock & Griffin, 2000; Pickering & Branigan, 1998). Complementary findings in the language comprehension literature suggest that prior exposure to a sentence with the same syntactic structure facilitates sentential processing (Arai, van Gompel, & Scheepers, 2007; Branigan, Pickering, & McLean, 2005; Ledoux, Traxler, & Swaab, 2007; Traxler, 2008) and can even bias subsequent interpretation of temporarily ambiguous sentences (Thothathiri & Snedeker, 2008). It is noteworthy that this short-term priming of syntax in comprehension is most readily observed when the sentences share lexical items (Tooley & Traxler, 2010). By contrast, lexically independent structural priming is thought to reflect a type of long-lasting procedural learning (Bock & Griffin, 2000), that is independent of episodic or declarative memory (Ferreira, Bock, Wilson, & Cohen, 2008), and can be explained by error-based learning mechanisms (Bernolet & Hartsuiker, 2010; Chang et al., 2006).

Similarly, experience with syntactic structures—low frequency structures in particular—supports subsequent processing of those structures over longer timescales (Fine & Florian Jaeger, 2013; Luka & Barsalou, 2005; Kaschak & Glenberg, 2004; Wells et al., 2009). Learners seem to adapt their syntactic expectations to the cumulative statistics of the experimental environment and this allows them to process low-frequency, but locally probable syntactic structures more easily (Fine et al., 2013). Here we show that listeners can track more than just the base rates of syntactic structures but also the frequencies of structure-verb conjunctions.

Critically, our training materials exposed participants to the instrument- and modifier-attachment interpretations with equal frequency, thus it is only by binding these attachment preferences to specific verbs, that participants were able to learn, and use these regularities to support subsequent processing. Our findings extend prior work showing that speakers can be primed to produce specific verbs with particular structures (Coyle & Kaschak, 2008), to the comprehension of a global syntactic ambiguity that is associated with two meaning-inconsistent alternatives. By placing the test of verb bias in the context of global ambiguity, we are able to show that the newly learned biases guide listeners to distinct ultimate interpretations of the sentence.

Furthermore, the training effect was present even when training and test trials for a given verb were nonadjacent, suggesting that our findings do not simply reflect lexically dependent, trial-to-trial priming. Rather, participants in our study seem to be accumulating statistics about which structure each verb is more likely to participate in, and holding onto those statistics over time. This finding is consistent with evidence that exposure to a given syntactic structure leads speakers to produce that structure in the future, even across intervening delays (Bock & Griffin, 2000), as well as evidence that exposure to a given syntactic structure facilitates listeners' subsequent processing of that structure, even after a delay (Tooley et al., 2014; Tooley, Traxler, & Swaab, 2009). Our findings show that verb-specific learning persists across delays with intervening items as well.

Our results go beyond the existing literature in several ways. First, we place participants in a situation reminiscent of daily exposure to language where listeners are flooded with a mixture of the same structures, competing structures, and unrelated structures, and, critically, they must select an action plan based on the interpretation they choose. Second, the delays examined here are much longer (average: 13 trials, median: 6 trials) than any previously used (e.g., a maximum of three trials in Tooley et al., 2014) in the literature. Third, the use of sentences with global ambiguity allows a more straightforward interpretation of what participants are encoding. Finally, unlike previous examinations of implicit learning of syntax (e.g., Fine et al., 2013; Tooley et al., 2014), which have focused on the reduced processing cost of a low-frequency structure after repeated exposure to that structure, we show that one set of verbs can be bound to one structure and a different set can be bound to the opposite structure through exposure to the statistics of the learning environment.

The Complementary Roles of Distributional and Semantic Learning in Verb Bias

The choice of a syntactic structure, and therefore, the frequency of a structure occurring with a verb, is often determined in part by the intended meaning of a sentence. In fact, it has been argued that the lexical bias of a verb may be the result of the relative frequencies of meanings with which a verb appears (Hare, Elman, Tabaczynski, & McRae, 2009; Hare, McRae, & Elman, 2003; Roland & Jurafsky, 2002). For instance, the literal meaning of *grasp* is typically followed by a direct object (e.g., Anna grasped the railing), whereas the metaphorical meaning is more likely to be followed by a sentential complement (e.g., Anna grasped that she had walked in on an awkward conversation). The overall lexical bias may then reflect which of the two meanings—literal or metaphorical—is used more commonly. These verb-specific structural expectations conditional on sense differences may be present not only in the case of syntactic alternatives that lead to two categorically different semantic interpretations (e.g., the ambiguous *with* phrases used in the experiments presented her), but also with syntactic alternations that are sometimes thought of as having meaning-equivalency. For example, in the case of the dative alternation, the double object structure, *The teacher gave the boy a book*, and the prepositional object structure, *The teacher gave a book to the boy*, lend themselves to different semantic interpretations (Arnold, Losongco, Wasow, & Ginstrom, et al., 2000; Pinker, 1989). On an information structure account (e.g., Arnold et al., 2000), *The teacher gave the boy a book* would be an appropriate response to *What did the teacher give to the boy?*, whereas *The teacher gave a book to the boy*, would be dispreferred, suggesting that their meanings are not equivalent. These nuances in meaning may contribute to the different rates of use of the structures.

However, verb-structure co-occurrence statistics and semantics may have a bidirectional relationship, such that not only do intended meanings determine which structures are most often used with a given verb, but frequency of co-occurrence between a verb and a structure may affect the weighting of different concepts in the representations of verbs, thereby altering the verb's semantic interpretation. In other words, learning the structural bias in Experiment 2 may involve learning a new *semantic* bias for a given verb as well; attaching a with-phrase to the verb invokes an instrument in the described event, attaching a with-phrase to the noun highlights a distinguishing property of the referent. Thus, the new distributional information is likely to have an effect both on the structural preference of the verb and its meaning.

An open question for future research is whether this semantic information transfers to new contexts and syntactic constructions that the verb participates in. Shafto, Havasi, and Snedeker (2014) showed that biases about novel verb semantics—whether they encode manner of motion or path—were shaped by the relative proportions of these alternatives during exposure. The larger the proportion of path-marking novel verbs present during the experiment, the more adults demonstrated a path bias at test. However, the extent to which the semantics of verbs with existing meanings can be altered as a result of co-occurrence with certain syntactic structures is not yet known. For example, would repeated exposure to *choose with* . . . in an instrument-meaning frame cause listeners to infer an instrument when the verb is used without the ambiguous *with*-phrase (e.g., *Choose the first one*)?

Verb Bias Learning and Context

More generally, while some previous findings show that exposure can produce long-lasting learning of syntactic structures (Bock & Griffin, 2000), and that learning can generalize across talkers (Thothathiri & Snedeker, 2008), an open question is whether the learning effects reported here would generalize to new environments and talkers. Alternatively, the verb-specific learning of semantic-syntactic preferences may be highly context-marked and limited to the experimental context or even the specific talker. Characterizing the generalizability of the observed learning effects may speak to the degree to which extralinguistic, contextual information is bound in memory with this newly learned syntactic-semantic bias information. If learning generalizes, it would suggest that it is not strongly context-bound. Kutta and Kaschak (2012) provide evidence that cumulative syntactic priming in language production is robust to changes in environment (but not to changes in the type of task; Kaschak, Kutta, & Coyle, 2014). Whether this is true of comprehension as well remains an open question. The goals of the language user are likely different depending on the modality. During language production, the goal is presumably to say something comprehensible while minimizing cognitive effort. During comprehension it is to understand whatever construction is currently unfolding with minimal effort. In the face of myriad possibilities for the currently unfolding sentence, the comprehension system may be more likely to rely on context-specific memory as a way to prepare for the most likely structure.

Conclusion

Ambiguity resolution in sentence processing recruits multiple sources of information, including statistical information about the regularity with which individual verbs participate in one syntactic structure over another. Previous findings had demonstrated that adults and children alike are sensitive to the statistical bias for individual verbs to participate in one syntactic-semantic interpretation over the other (Snedeker & Trueswell, 2004), and that recent exposure to particular syntactic structures causes listeners to adapt subsequent processing to be consistent with the recent input (e.g., Thothathiri & Snedeker, 2008; Traxler, 2008). Here we show that listeners update calculations of these regularities in a verb-specific manner, and use this newly learned information to guide online processing of ambiguous sentences. This verb-specific learning is robust to interference from other structures and lexical items. The findings point to a role for lifelong tuning of verb syntactic and semantic representations, emphasizing the malleability of lexical representations and the significance of recent experience to syntactic ambiguity resolution. The main finding reported here, that listeners flexibly learn the verb biases present in the environment, is consistent with recent proposals that adaptation allows listeners to make sense of the tremendous variability in the input and is a key mechanism underlying language comprehension (Fine et al., 2013; Kleinschmidt & Jaeger, 2015). It also raises interesting questions about the complicated interplay between ongoing learning that leads to dynamically changing linguistic expectations and the core language representations that underlie comprehension processes.

References

Arai, M., van Gompel, R. P. G., & Scheepers, C. (2007). Priming ditransitive structures in comprehension. *Cognitive Psychology, 54,* 218–250. http://dx.doi.org/10.1016/j.cogpsych.2006.07.001

Arnold, J. E., Losongco, T., Wasow, T., & Ginstrom, R. (2000). Heaviness vs. Newness: The effects of structural complexity and discourse status on constituent ordering. *Language, 76,* 28–55. http://dx.doi.org/10.1353/lan.2000.0045

Bernolet, S., & Hartsuiker, R. J. (2010). Does verb bias modulate syntactic priming? *Cognition, 114,* 455–461. http://dx.doi.org/10.1016/j.cognition.2009.11.005

Bock, J. K. (1986). Syntactic persistence in language production. *Cognitive Psychology, 18,* 355–387. http://dx.doi.org/10.1016/0010-0285(86)90004-6

Bock, K., & Griffin, Z. M. (2000). The persistence of structural priming: Transient activation or implicit learning? *Journal of Experimental Psychology: General, 129,* 177–192. http://dx.doi.org/10.1037/0096-3445.129.2.177

Boland, J. E. (1997). The relationship between syntactic and semantic processes in sentence comprehension. *Language and Cognitive Processes, 12,* 423–484. http://dx.doi.org/10.1080/016909697386808

Boland, J. E., Tanenhaus, M. K., Garnsey, S. M., & Carlson, G. N. (1995). Verb argument structure in parsing and interpretation: Evidence from wh-questions. *Journal of Memory and Language, 34,* 774–806. http://dx.doi.org/10.1006/jmla.1995.1034

Brainard, D. H. (1997). The psychophysics toolbox. *Spatial Vision, 10,* 433–436. http://dx.doi.org/10.1163/156856897X00357

Branigan, H. P., Pickering, M. J., & McLean, J. F. (2005). Priming prepositional-phrase attachment during comprehension. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 31,* 468–481. http://dx.doi.org/10.1037/0278-7393.31.3.468

Chang, F., Dell, G. S., & Bock, K. (2006). Becoming syntactic. *Psychological Review, 113,* 234–272. http://dx.doi.org/10.1037/0033-295X.113.2.234

Cohen, J., Cohen, P., West, S. G., & Aiken, L. S. (2003). *Applied multiple regression/correlation analysis for the behavioral sciences* (3rd ed.). Mahwah, NJ: Erlbaum, Publishers.

Coyle, J. M., & Kaschak, M. P. (2008). Patterns of experience with verbs affect long-term cumulative structural priming. *Psychonomic Bulletin & Review, 15,* 967–970. http://dx.doi.org/10.3758/PBR.15.5.967

Ferreira, V. S., Bock, K., Wilson, M. P., & Cohen, N. J. (2008). Memory for syntax despite amnesia. *Psychological Science, 19,* 940–946. http://dx.doi.org/10.1111/j.1467-9280.2008.02180.x

Fine, A. B., & Florian Jaeger, T. (2013). Evidence for implicit learning in syntactic comprehension. *Cognitive Science, 37,* 578–591. http://dx.doi.org/10.1111/cogs.12022

Fine, A. B., Jaeger, T. F., Farmer, T. A., & Qian, T. (2013). Rapid expectation adaptation during syntactic comprehension. *PLoS ONE, 8,* e77661. http://dx.doi.org/10.1371/journal.pone.0077661

Fisher, C. (1996). Structural limits on verb mapping: The role of analogy in children's interpretations of sentences. *Cognitive Psychology, 31,* 41–81. http://dx.doi.org/10.1006/cogp.1996.0012

Fisher, C., Gertner, Y., Scott, R. M., & Yuan, S. (2010). Syntactic bootstrapping. *Wiley Interdisciplinary Reviews: Cognitive Science, 1,* 143–149.

Fisher, C., Gleitman, H., & Gleitman, L. R. (1991). On the semantic content of subcategorization frames. *Cognitive Psychology, 23,* 331–392. http://dx.doi.org/10.1016/0010-0285(91)90013-E

Garnsey, S. M., Pearlmutter, N. J., Myers, E., & Lotocky, M. A. (1997). The contributions of verb bias and plausibility to the comprehension of temporarily ambiguous sentences. *Journal of Memory and Language, 37,* 58–93. http://dx.doi.org/10.1006/jmla.1997.2512

Gleitman, L. (1990). The structural sources of verb meanings. *Language Acquisition, 1,* 3–55. http://dx.doi.org/10.1207/s15327817la0101_2

Hallett, P. E. (1986). Eye movements. In K. R. Boff, L. Kaufman, & J. P. Thomas (Eds.), *Handbook of perception and human performance* (Vol. 1, pp. 10.1–10.112). New York, NY: Wiley.

Hare, M., Elman, J. L., Tabaczynski, T., & McRae, K. (2009). The wind chilled the spectators, but the wine just chilled: Sense, structure, and sentence comprehension. *Cognitive Science, 33,* 610–628. http://dx.doi.org/10.1111/j.1551-6709.2009.01027.x

Hare, M., McRae, K., & Elman, J. L. (2003). Sense and structure: Meaning as a determinant of verb subcategorization preferences. *Journal of Memory and Language, 48,* 281–303. http://dx.doi.org/10.1016/S0749-596X(02)00516-8

Kaschak, M. P., & Glenberg, A. M. (2004). This construction needs learned. *Journal of Experimental Psychology: General, 133,* 450–467. http://dx.doi.org/10.1037/0096-3445.133.3.450

Kaschak, M. P., Kutta, T. J., & Coyle, J. M. (2014). Long and short term cumulative structural priming effects. *Language and Cognitive Processes, 29,* 728–743. http://dx.doi.org/10.1080/01690965.2011.641387

Kim, C. S., Carbary, K. M., & Tanenhaus, M. K. (2014). Syntactic priming without lexical overlap in reading comprehension. *Language and Speech, 57,* 181–195. http://dx.doi.org/10.1177/0023830913496052

Kleiner, M., Brainard, D., & Pelli, D. (2007). What's new in Psychtoolbox-3? [ECVP Abstract Supplement]. *Perception, 36.*

Kleinschmidt, D. F., & Jaeger, T. F. (2015). Robust speech perception: Recognize the familiar, generalize to the similar, and adapt to the novel. *Psychological Review, 122,* 148–203. http://dx.doi.org/10.1037/a0038695

Kutta, T. J., & Kaschak, M. P. (2012). Changes in task-extrinsic context do not affect the persistence of long-term cumulative structural priming. *Acta Psychologica, 141,* 408–414. http://dx.doi.org/10.1016/j.actpsy.2012.09.007

Ledoux, K., Traxler, M. J., & Swaab, T. Y. (2007). Syntactic priming in comprehension: Evidence from event-related potentials. *Psychological Science, 18,* 135–143. http://dx.doi.org/10.1111/j.1467-9280.2007.01863.x

Luka, B. J., & Barsalou, L. W. (2005). Structural facilitation: Mere exposure effects for grammatical acceptability as evidence for syntactic priming in comprehension. *Journal of Memory and Language, 52,* 436–459. http://dx.doi.org/10.1016/j.jml.2005.01.013

MacDonald, M. C., Pearlmutter, N. J., & Seidenberg, M. S. (1994). The lexical nature of syntactic ambiguity resolution [corrected]. *Psychological Review, 101,* 676–703. http://dx.doi.org/10.1037/0033-295X.101.4.676

Naigles, L. (1990). Children use syntax to learn verb meanings. *Journal of Child Language, 17,* 357–374. http://dx.doi.org/10.1017/S0305000900013817

Pelli, D. G. (1997). The VideoToolbox software for visual psychophysics: Transforming numbers into movies. *Spatial Vision, 10,* 437–442. http://dx.doi.org/10.1163/156856897X00366

Pickering, M. J., & Branigan, H. P. (1998). The representation of verbs: Evidence from syntactic priming in language production. *Journal of Memory and Language, 39,* 633–651. http://dx.doi.org/10.1006/jmla.1998.2592

Pinker, S. (1989). *Learnability and cognition: The acquisition of argument structure*. Cambridge, MA: MIT Press.

Qi, Z., Yuan, S., & Fisher, C. (2011). Where does verb bias come from? Experience with particular verbs affects on-line sentence processing. In N. Danis, K. Mesh, & H. Sung (Eds.), *Proceedings of 35th Boston University Conference on Language Development* (pp. 500–512). Somerville, MA: Cascadilla Press.

Roland, D., & Jurafsky, D. (2002). Verb sense and verb subcategorization probabilities. In P. Merlo & S. Stevenson (Eds.), *The lexical basis of sentence processing: Formal, computational and experimental issues* (pp. 325–345). Amsterdam, the Netherland: John Benjamins. http://dx.doi.org/10.1075/nlp.4.17rol

Shafto, C. L., Havasi, C., & Snedeker, J. (2014). On the plasticity of semantic generalizations: Children and adults modify their verb lexicalization biases in response to changing input. *Developmental Psychology, 50,* 794–808. http://dx.doi.org/10.1037/a0034253

Snedeker, J., & Gleitman, L. (2004). Why it is hard to label our concepts. In D. G. Hall & S. R. Waxman (Eds.), *Weaving a lexicon* (pp. 257–294). Cambridge, MA: MIT Press.

Snedeker, J., & Trueswell, J. C. (2004). The developing constraints on parsing decisions: The role of lexical-biases and referential scenes in child and adult sentence processing. *Cognitive Psychology, 49,* 238–299. http://dx.doi.org/10.1016/j.cogpsych.2004.03.001

Spivey, M. J., & Tanenhaus, M. K. (1998). Syntactic ambiguity resolution in discourse: Modeling the effects of referential context and lexical frequency. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 24,* 1521–1543. http://dx.doi.org/10.1037/0278-7393.24.6.1521

Spivey-Knowlton, M., & Sedivy, J. C. (1995). Resolving attachment ambiguities with multiple constraints. *Cognition, 55,* 227–267. http://dx.doi.org/10.1016/0010-0277(94)00647-4

Spivey-Knowlton, M. J., Trueswell, J. C., & Tanenhaus, M. K. (1993). Context effects in syntactic ambiguity resolution: Discourse and semantic influences in parsing reduced relative clauses. *Canadian Journal of*

Experimental Psychology, 47, 276–309. http://dx.doi.org/10.1037/h0078826

Taraban, R., & McClelland, J. L. (1988). Constituent attachment and thematic role assignment in sentence processing: Influences of content-based expectations. *Journal of Memory and Language, 27,* 597–632. http://dx.doi.org/10.1016/0749-596X(88)90011-3

Thothathiri, M., & Snedeker, J. (2008). Give and take: Syntactic priming during spoken language comprehension. *Cognition, 108,* 51–68. http://dx.doi.org/10.1016/j.cognition.2007.12.012

Tooley, K. M., Swaab, T. Y., Boudewyn, M. A., Zirnstein, M., & Traxler, M. J. (2014). Evidence for priming across intervening sentences during on-line sentence comprehension. *Language and Cognitive Processes, 29,* 289–311.

Tooley, K. M., & Traxler, M. J. (2010). Syntactic priming effects in comprehension: A critical review. *Language and Linguistics Compass, 4,* 925–937. http://dx.doi.org/10.1111/j.1749-818X.2010.00249.x

Tooley, K. M., Traxler, M. J., & Swaab, T. Y. (2009). Electrophysiological and behavioral evidence of syntactic priming in sentence comprehension. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 35,* 19–45. http://dx.doi.org/10.1037/a0013984

Traxler, M. J. (2008). Lexically independent priming in online sentence comprehension. *Psychonomic Bulletin & Review, 15,* 149–155. http://dx.doi.org/10.3758/PBR.15.1.149

Trueswell, J. C. (1996). The role of lexical frequency in syntactic ambiguity resolution. *Journal of Memory and Language, 35,* 566–585. http://dx.doi.org/10.1006/jmla.1996.0030

Trueswell, J. C., Tanenhaus, M. K., & Kello, C. (1993). Verb-specific constraints in sentence processing: Separating effects of lexical preference from garden-paths. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 19,* 528–553. http://dx.doi.org/10.1037/0278-7393.19.3.528

Wells, J. B., Christiansen, M. H., Race, D. S., Acheson, D. J., & MacDonald, M. C. (2009). Experience and sentence processing: Statistical learning and relative clause comprehension. *Cognitive Psychology, 58,* 250–271. http://dx.doi.org/10.1016/j.cogpsych.2008.08.002

Appendix A

List of the 27 Target Verbs by Category

Verb	Relevant	Instrument	Category	Animal 1	Animal 2	Instrument 1	Instrument 2
Strike	95%	95%	Instrument-biased	Bear	Elephant	Necklace	Umbrella
Whack	92%	95%	Instrument-biased	Cow	Ladybug	Fan	Pencil
Hit	97%	92%	Instrument-biased	Frog	Mouse	Cup	Tube
Rub	84%	90%	Instrument-biased	Butterfly	Panda	Crayon	Violin
Poke	98%	88%	Instrument-biased	Bunny	Pig	Spoon	Violin
Bop	92%	87%	Instrument-biased	Elephant	Panda	Napkin	Spoon
Smack	91%	87%	Instrument-biased	Dog	Leopard	Flute	Hat
Clean	99%	86%	Instrument-biased	Dog	Turtle	Leaf	Violin
Tease	86%	86%	Instrument-biased	Dog	Leopard	Crayon	Lollipop
Feed	49%	71%	Equibiased	Duckling	Zebra	Book	Lollipop
Scuff	92%	71%	Equibiased	Chicken	Pig	Cup	Flower
Pinch	76%	68%	Equibiased	Leopard	Panda	Hat	Toothbrush
Knock on	84%	67%	Equibiased	Bunny	Frog	Feather	Sponge
Pat	84%	65%	Equibiased	Dog	Leopard	Flower	Pencil
Locate	93%	64%	Equi-biased	Camel	Penguin	Straw	Tube
Feel	74%	62%	Equibiased	Bear	Leopard	Candle	Pen
Spot	93%	62%	Equibiased	Bird	Lion	Pencil	Straw
Point to	88%	61%	Equibiased	Fish	Penguin	Funnel	Leaf
Pet	81%	38%	Modifier-biased	Dolphin	Lion	Sponge	Tongs
Look at	84%	35%	Modifier-biased	Chicken	Horse	Leaf	Spoon
Squeeze	81%	35%	Modifier-biased	Bunny	Zebra	Hat	Microphone
Pick out	92%	33%	Modifier-biased	Duckling	Ladybug	Net	Straw
Cuddle	71%	30%	Modifier-biased	Dolphin	Whale	Microphone	Pen
Find	94%	28%	Modifier-biased	Bird	Lion	Mitten	Towel
Hug	70%	23%	Modifier-biased	Giraffe	Panda	Party hat	Umbrella
Select	90%	11%	Modifier-biased	Squirrel	Zebra	Party hat	Towel
Choose	96%	6%	Modifier-biased	Cow	Squirrel	Barrette	Pen

Note. Results of the Norming Study for each verb are reported in terms of the percentage of responses that were relevant to the attachment ambiguity and the percentage of the relevant responses that indicated an instrument interpretation (VP-Attachment). The Animals (1, 2) and Instruments (1, 2) were paired with the verb in different combinations across the two test lists.

(*Appendices continue*)

Appendix B

List of the Eight Verbs Used in Experiment 2 and the Corresponding Action Data From Experiment 1 and the Two Training Conditions in Experiment 2

Verb	Proportion of clicks on target instrument in Experiment 1	Proportion of clicks on target instrument in Experiment 2 after Instrument training	Proportion of clicks on target instrument in Experiment 2 after Modifier training
Squeeze	.31	.65	.34
Pinch	.33	.54	.22
Feel	.46	.63	.59
Hug	.46	.52	.31
Cuddle	.52	.46	.58
Rub	.52	.66	.68
Knock on	.58	.68	.53
Clean	.6	.81	.64

Note. The eight verbs were selected to be the most equibiased based on action and eye-fixation data from Experiment 1.

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