Syntactic Adaptation and Word Learning in Children and Adults

Abstract

Syntactic adaptation may be a key mechanism underlying children's learning of novel words. Havron et al. (2019) exposed French-speaking children (ages 3 to 4) to a speaker biased by the use of either familiar verbs or nouns presented in the same syntactic context. This influenced participants' interpretations of ambiguous novel words presented in the same syntactic frame. In Experiment 1, we successfully replicated Havron et al. with 77 French-speaking adults, using a web-based eye-tracking paradigm. Experiment 2 adapted this paradigm to English, finding that repeated exposure to a syntactic structure induced 102 English-speaking adults to update their expectations about the meanings of novel words. Experiment 3 found similar evidence of syntactic adaptation in 74 three- to five-year-old English-speaking children. The results indicate that participants adapted to the specific linguistic structure used, not just the speaker's tendency to mention actions or objects. These findings support the role of rapid adaptation during word learning and demonstrate the feasibility of conducting eye-tracking studies through online platforms.

Background

How do children learn language so quickly? In just a few years, children are able to learn how to segment a continuous speech stream into words and phrases and map these utterances to their meanings. To do this, children cannot simply be passive observers of the world around them; they are instead flexible and active learners who draw on powerful learning mechanisms during development (Denison & Xu, 2019; Gopnik & Bonawitz, 2015; Krogh et al., 2013; Raz & Saxe, 2020; Schulz, 2012; Xu, 2019; Xu & Tenenbaum, 2007). One of these possible learning

mechanisms is the ability to track linguistic patterns in the speech of others and rapidly adapt to these patterns. While such linguistic adaptation is increasingly well studied in adults (Bradlow & Bent, 2008; Chang et al., 2006; Fine et al., 2013; D. F. Kleinschmidt & Jaeger, 2015; Kraljic & Samuel, 2007; Ostrand & Ferreira, 2019; Prasad & Linzen, 2021; Ryskin et al., 2019; Schuster & Degen, 2020; Yildirim et al., 2016), the question of whether linguistic adaptation may be a mechanism supporting language acquisition remains understudied.[1]

Havron, de Carvalho, Fiévet, & Christophe (2019) were the first to directly investigate children's capacity to infer novel word meanings by adapting to specific syntactic structures. Their findings demonstrated that French-speaking adults and children showed signs of rapid syntactic adaptation after repeated exposure to a particular sentence structure. Furthermore, participants drew on these expectations to guide their learning of unfamiliar words that were presented in the same syntactic context. In this paper, we describe three experiments that replicate the findings of Havron et al. (2019) in a web-based eye-tracking paradigm and extend the findings to English-speaking adults and children. These studies build on two main lines of work: a) syntactic priming (specifically, adaptation) and b) syntactic bootstrapping during language acquisition.

Syntactic priming in adults is a well-established phenomenon, in which exposure to a particular sentence structure increases the likelihood of participants producing that structure themselves (*syntactic alignment:* Bock, 1986; Branigan et al., 2000, 2007; Cleland & Pickering, 2003; Ostrand & Ferreira, 2019; Pickering & Garrod, 2004*)* and expecting utterances they hear to contain the structure (*syntactic adaptation:* Fine et al., 2013; Fine & Jaeger, 2013; Kamide, 2012; Lu et al., 2021; Prasad & Linzen, 2021). On the production side, experimental studies have

[1] Though theories of statistical learning in language acquisition are closely related (e.g., Balcan & Feldman, 2014; Mcmurray et al., 2009; Vallabha et al., 2007).

long shown that participants tend to align their syntactic structures in dialogue (Bock, 1986). For instance, adults who heard sentences containing dative verbs with either a prepositional object (e.g. *The pirate handed the cake to the sailor*) or a direct object (e.g. *The pirate handed the sailor the cake*) were more likely to subsequently produce descriptions of pictures that used the same dative structure they had heard previously (Branigan et al., 2000; Cleland & Pickering, 2003). Participating actively in a dialogue, rather than listening as a side participant, has been linked to a greater degree of alignment (Branigan et al., 2007). Syntactic alignment effects have also been found with datives and verb particle placement (e.g., *John picked up the book* vs. *John picked the book up*) in a corpus of naturalistic dialogue (Gries, 2005). This finding indicates that syntactic priming is not merely a product of experimental settings but is also a hallmark of natural communication.

In addition, syntactic priming effects have increasingly been investigated in comprehension (Pickering & Ferreira, 2008)—that is, as syntactic adaptation. Fine et al. (2013) used a self-paced reading paradigm to examine participants' comprehension of "garden path sentences," such as *The experienced soldiers warned about the dangers conducted the midnight raid,* which typically cause delays in language processing. After repeated exposures to these sentences, participants adapted to the new syntactic distribution, reducing or even eliminating the processing disadvantage (though cf. Harrington Stack et al., 2018). Similarly, adaptation has been proposed as a mechanism underlying satiation effects, where upon repeated exposure listeners are more likely to judge ungrammatical sentences as acceptable (Lu et al., 2021). Evidence from fMRI (Noppeney & Price, 2004; Segaert et al., 2013) and ERP (Ledoux et al., 2007) studies corroborates the finding that syntactic priming facilitates comprehension of difficult-to-process sentences. Research involving eye-tracking has found that syntactic

adaptation can also guide understanding of syntactically ambiguous utterances, with participants interpreting utterances as being consistent with the type of structure they previously heard (Kamide, 2012).

These syntactic priming effects appear to be not just the result of transient activation of representations, but rather a form of learning that can have long-term, cumulative effects. Using a similar picture task as (Bock, 1986) to elicit sentences containing dative verbs, Boyland & Anderson (1998) found that syntactic priming still occurred when there was a 20-minute delay between the priming stage and participants' productions. Even studies in which syntactic priming took place days before the test stage have reported that participants exhibited adaptation to difficult sentence structures, such as ambiguous relative clauses, and came to process them more quickly (Long & Prat, 2008; Wells et al., 2009). Furthermore, even rapid syntactic priming appears to be cumulative, meaning that greater exposure to a particular sentence structure leads to an incrementally larger processing advantage (Fine & Jaeger, 2016; Kaschak, 2007). These cumulative and long-term effects support an explanation of syntactic priming that is linked to implicit learning about the distributions of sentence structures, rather than immediate, short-lived activation of representations (Bock & Griffin, 2000; Branigan & Messenger, 2016). Additional evidence for the implicit learning account stems from the finding that the change in listeners' syntactic expectations is influenced by the size of the error signal accompanying a particular syntactic prime (Fine & Jaeger, 2013). Recently, syntactic adaptation has also been modeled as a process of rational belief update, in which the reliability of a cue is taken into account to determine whether listeners should update their expectations (Kleinschmidt et al., 2012). Moreover, some studies have suggested that syntactic priming is speaker-specific (Kamide, 2012; Kroczek & Gunter, 2017; Lu et al., 2021; Yildirim et al., 2016), though others have failed

to find such effects (Liu et al., 2017; Ostrand & Ferreira, 2019). It is clear, however, that syntactic priming, whether alignment or adaptation, involves long-term and potentially sophisticated tracking of syntactic distributions.

Syntactic alignment and adaptation have the potential to act as a powerful support for children's language acquisition. Many studies have shown that infants and children are able to engage in statistical learning, meaning that they can extract statistical regularities from an input (Arnon, 2019; Krogh et al., 2013; Romberg & Saffran, 2010; J. Saffran & Kirkham, 2017). For instance, Saffran et al.(1996) found evidence that 8-month-old infants could segment words from a continual speech stream on the basis of transitional probabilities between syllables. This occurred after only two minutes of exposure to the speech signal, indicating that even very young infants have a powerful learning mechanism that is sensitive to statistical information in the environment. Older children, too, exhibit statistical learning, with some studies suggesting that performance increases with age (Arciuli & Simpson, 2011; Shufaniya & Arnon, 2018).

Such a mechanism could also allow children to rapidly adapt to syntactic patterns in the language input. Indeed, multiple studies have demonstrated that children are sensitive to syntactic priming, although these effects are sometimes more difficult to detect than with adults depending on the task demands (Shimpi et al., 2007). Peter et al., (2015) reported that children ages three to six and adults showed effects of syntactic alignment with datives, during a task where they were prompted to describe cartoon animations. Children have also been shown to align with active- and passive-voice sentences, producing more sentences of the type they were previously exposed to (Bencini & Valian, 2008; Messenger et al., 2011).

In addition to alignment studies, children are sensitive to syntactic priming in comprehension—that is, syntactic adaptation. Thothathiri & Snedeker (2008) used an eye-

tracking paradigm to measure children's expectations about temporarily ambiguous datives (e.g., direct object: *Show the horse the book* vs. prepositional object: *Show the horn to the dog*). When children had been primed with either DO or PO sentences, they were more likely to interpret a temporarily ambiguous phrase (such as *Show the hor—*) in a manner consistent with the structure used during priming. Like adults, children have also shown cumulative effects of syntactic adaptation over the course of an experiment (Huttenlocher et al., 2004), including when the priming stimuli used nonsense verbs (Brooks & Tomasello, 1999). Branigan & Messenger (2016) found a difference between adaptation effects in children and adults: While both groups showed immediate effects of syntactic adaptation, only children demonstrated significant *cumulative* effects in a second session a week later. Relatedly, (Rowland et al., 2012) demonstrated that the magnitude of the priming effect was larger for young children than for older children and adults. These results suggest that, at least in some contexts, children's expectations about sentence structure may be more uncertain or more flexibly updated than adults' expectations. This greater ability to adapt could help children learn more quickly in unfamiliar linguistic contexts. Thus, it is reasonable to propose that syntactic adaptation may play a role in not just children's sentence processing, but also their acquisition of language.

To examine how syntactic adaptation may support language acquisition, our experiments also draw on work that shows evidence of syntactic bootstrapping in children's word learning. Syntactic bootstrapping is a process by which children can infer the meanings of unfamiliar words partially based on their syntactic characteristics (Gleitman, 1990). For example, upon hearing a sentence such as *It's daxing*, a child can use the *-ing* affix to infer that *dax* refers to an action and is therefore a verb. Eye-tracking studies have shown that children as young as 24 months are sensitive to the syntactic context of novel words and draw on syntactic cues to help

them construe images of scenes (Waxman et al., 2009). Furthermore, while listening to temporarily ambiguous utterances, preschoolers demonstrate predictive eye movements that are influenced by syntactic characteristics of words, such as transitive vs. intransitive verbs (Gambi et al., 2016). Huang & Arnold (2016) found a correlation in which children who were more sensitive to syntactic cues had more accurate interpretations of novel words, which suggests that syntax may play an important role in successful word learning for children.

Further studies have indeed confirmed that syntactic bootstrapping supports children's acquisition of novel words. Syntax appears to be one of the characteristics of words that children are sensitive to during word learning (Dautriche et al., 2015). To directly examine the effects of cues from syntax, Yuan & Fisher (2009) played sentences containing novel words that were either transitive (e.g., *She blicked the baby*) or intransitive (e.g., *She blicked*). They found that two-year-olds who heard transitive sentences looked longer at pictures with two people in them rather than one, which indicated that they used syntactic cues (i.e. presence of a direct object in transitive sentences) to interpret the novel words. Using a similar eye-tracking paradigm, studies have reported that 18-month-olds (He & Lidz, 2017) and 23-month-olds (Bernal et al., 2007) can use syntactic cues from phrases such as *It's pooning* vs. *It's a poon* to map novel words to images portraying either actions or objects, respectively. Thus, there is evidence that children are not just sensitive to syntactic cues, but also actively draw on them during word learning. These findings have led researchers to propose a probabilistic model that uses syntactic bootstrapping to acquire syntactic categories (Christophe et al., 2016). Such a model performed very well in a word-learning task using a corpus of French child-directed speech, even with minimal semantic knowledge. This suggests that syntactic bootstrapping is a viable mechanism underlying children's word learning.

To sum up, both children and adults exhibit syntactic adaptation in comprehension and production. In addition, syntactic cues play a key role in children's word learning via a process of syntactic bootstrapping. Havron et al. (2019) brought these two lines of work together by investigating whether syntactic adaptation is a driving force in children's acquisition of novel words. The connection between adaptation and acquisition is motivated by prior work: for instance, Chang et al. (2006) developed a connectionist model of sentence production that used error-based learning to imitate the acquisition of syntax. That is, after encountering a violation of its predictions, the model updated its expectations about upcoming syntactic material. This model was able to account for many syntactic priming effects in adults and children, including the finding that more surprising structures are associated with larger priming effects (Bernolet & Hartsuiker, 2010; Fine & Jaeger, 2013; Jaeger & Snider, 2013).

This work suggests that encountering an unexpected distribution of syntactic structures could lead children to update their expectations and, importantly, recruit those expectations during word learning. For example, in a naturalistic context, a child might hear an adult describing a toy dog using repeated similar syntactic frames, such as *The dog is running, The dog is playing,* etc. Adapting to the use of this syntactic frame would allow the child to more easily learn a novel word presented in the same frame. This mechanism has the potential to unify accounts of adaptation in language processing with accounts of language acquisition, which was a key motivation for Havron et al. (2019).

Specifically, Havron et al. (2019) examined whether priming French children with a particular syntactic structure would influence the meaning they assigned to novel words in an ambiguous context. During training trials, three- and four-year-old children were exposed to repeated trials of a French phrase (*La petite*) that can be followed by either a noun or a verb (e.g.,

La petite grenouille [The little frog] vs. *La petite dort [The little one sleeps]*). On test trials, children heard novel words presented in the same syntactic frame (e.g., *La petite nuve*), and their eye movements were measured to see whether children looked more at an image depicting a novel object or an image depicting a novel action. The results confirmed that children (and an adult comparison group) did indeed appear to update their predictions about which syntactic structure a speaker would use, and they drew on these predictions to infer the meaning of a novel word.

The studies reported here build on the work of Havron et al. (2019) in several ways. First, in Experiment 1, we tested whether these results would directly replicate in a new context: an eye-tracking study conducted entirely online, with adults. Next, we conducted a crosslinguistic replication of the study in English, using a syntactic frame (*The girls/The girl's*) that can similarly be followed by either a noun or a verb (e.g., *The girls sleep* vs. *The girl's book*). We first ran this study online with adults (Experiment 2) and then carried it out with three- to five-year-old children (Experiment 3). These studies examined whether the results of Havron et al. (2019) would replicate in a different language and using novel methods: eye-tracking in a web-based environment. Thus, Experiment 1 provides a validation of the novel method, while Experiments 2 and 3 constitute a cross-linguistic test of the main hypothesis: if syntactic adaptation is a mechanism underlying word learning, upon encountering an unfamiliar word English speaking adults and children should look more at the image (action or object) that matched the type of phrase (verb or noun) they had heard during training trials

We preregistered all three experiments on the Open Science Foundation at: https://osf.io/3j6rw/. All stimuli, data, and analyses for Experiments 1, 2, and 3 can be found at: https://github.com/eswanson166/syntactic-adaptation-and-word-learning.

Experiment 1

Experiment 1 was a direct replication of Havron et al. (2019) that was carried out using web-based eye-tracking. This served the dual purpose of both replicating the original study and validating web-based eye-tracking as a paradigm suitable for studying the interaction of syntactic bootstrapping and adaptation.

Methods

Participants

We collected data from 77 participants (31 female; 46 male) using Prolific, an online crowdsourcing website. All were adults who reported speaking French as their first language.

Procedure and Materials

A diagram of the experimental set-up is shown in Figure 1. The stimuli used in the study, as well as the structure of the trials, were identical to those used in Havron et al. (2019). Every participant was randomly assigned to either the noun condition (37) or the verb condition (40). Participants first completed a 9-point calibration, which was adapted from the original study to work with the web-based eye-tracking Javascript library WebGazer (Papoutsaki et al., 2016). The study consisted of two phases: a training phase and a test phase. The total experiment included ten trials and lasted about twelve minutes.

On each training trial, all participants saw two videos. One showed a girl performing a familiar action (such as jumping), while the other was of the same girl holding a familiar object (such as a toy car). The structure of each training trial was identical. First, the participant saw a preview of one video only, followed by a preview of the other video. Then, during the contrast

phase, the participant saw both videos together. For these parts of the trial, a female narrator told the child to look at the videos in a child-friendly voice, but she did not comment on what the videos depicted. The last part of the trial was the event phase, during which children saw both videos again, but the narrator described what was in just one of the two videos. If participants were in the noun condition, she said a phrase such as *La petite grenouille* ("The little frog"). If participants were in the verb condition, she said a phrase such as *La petite dort* ("The little one (feminine) is sleeping"). Thus, participants in both conditions heard the same syntactic frame: *La petite [X],* but it was followed by either a noun (meaning "The little X") or a verb (meaning "The little one is Xing"). Participants were exposed to four training trials. The side of the screen where the target video appeared was counterbalanced, and the order of the training trials was randomized.

Figure 1

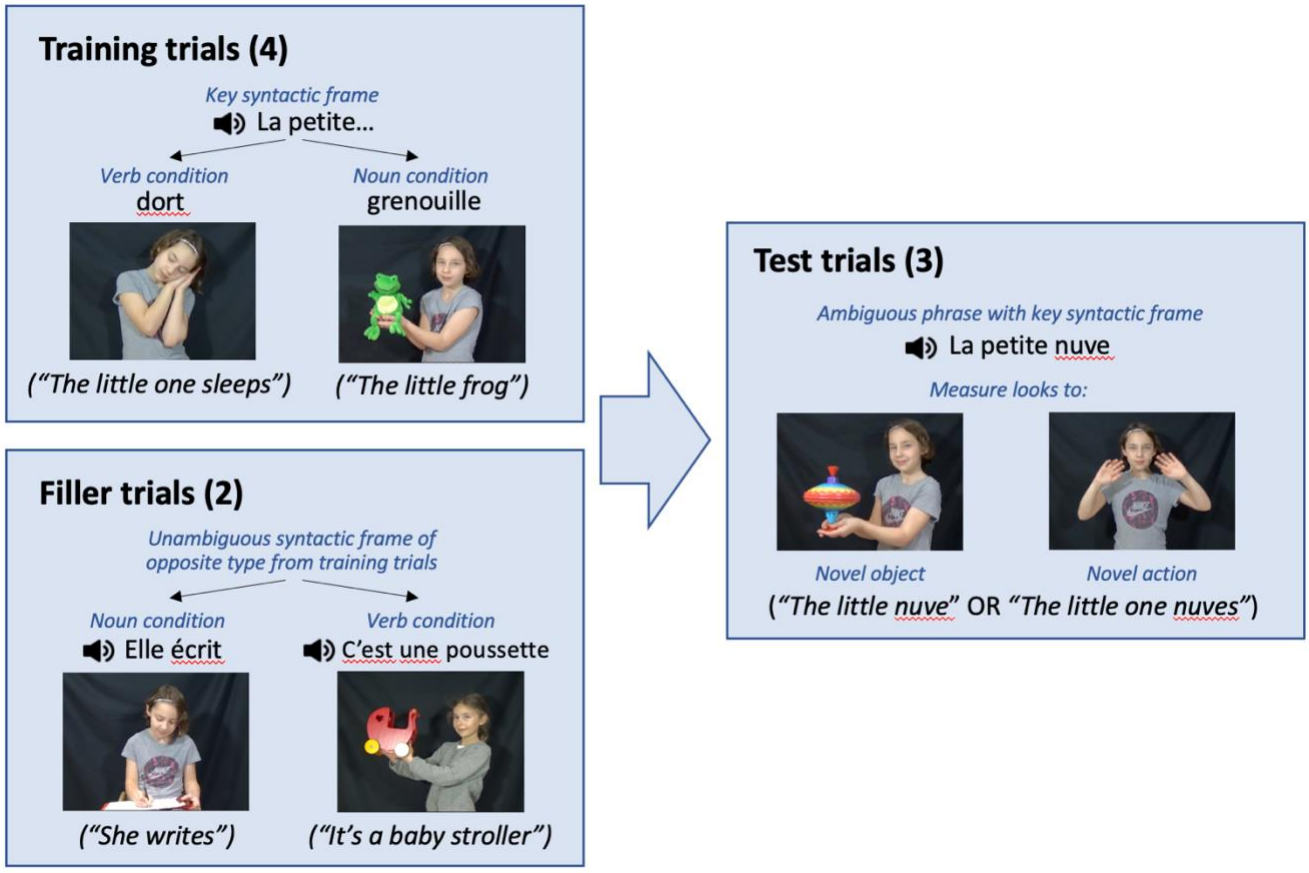


Diagram of experimental set-up for Experiment 1. Participants saw two training trials, followed by two filler trials, followed by the other two training trials, and then saw all three test trials. The order of the trials within these blocks was randomized.

In between the first two training trials and the last two training trials, participants watched two filler trials. These trials had the same structure as the training trials except that the narrator referred to the type of video that was *not* referred to in the training trials, using a structure that was unambiguous. Therefore, participants in the noun condition heard a description of the action video in a sentence such as *Elle écrit* ("She writes"), since *Elle…* cannot be followed by a noun. Similarly, participants in the verb condition heard a description of the object video in a sentence such as *C'est une poussette* ("It's a baby-stroller"), because *C'est une…*

cannot precede a verb. These filler trials were included so that participants would understand that the narrator could refer to either the action video or the object video. It was simply with the structure *La petite…* that the narrator was biased toward using either nouns or verbs. This also reduced the possibility that participants would look toward the action or object video on test trials purely because they were used to looking at that type of video.

After the training trials, all participants watched three test trials, which were identical regardless of condition (though the order was again randomized). Test trials had the same structure as training trials, but the two videos depicted a novel object and a novel action. Also, participants heard the narrator's description once before the event phase started so that looks could be measured from the beginning of the event phase. The narrator used the same *La petite…* context as before, but it was followed by an unfamiliar word that does not actually exist in French, such as *La petite nuve.* Since *La petite…* can be followed by a noun or a verb, participants could in principle interpret *nuve* as a noun or a verb. However, if participants adapt to the structure preferred by the speaker during training trials, they should behave differently in the differenc conditions. In particular, they should interpret novel words as nouns in the noun condition, and therefore look more at the object video during test trials; and conversely, they should interpret novel words as verbs in the verb condition, and therefore look more at the action video during test trials. In line with previous eye-tracking studies, we considered a greater proportion of looks to a video to be an indicator that participants interpreted the word as matching what was depicted in the video.

As in Havron et al. (2019), there was also one trial at the end of the experiment which used the structure *Le petit [X],* the masculine form of the *La petite [X]* structure, and which

showed videos depicting a boy rather than a girl. This was an exploratory trial to examine whether the adaptation effect would generalize to a slightly different structure.

Measures

We measured participants' eye movements using WebGazer, a program that estimates the coordinates of participants' eye movements on the computer screen using a webcam (Papoutsaki et al., 2016). WebGazer is a novel method for conducting eye-tracking studies, and as a direct replication of Havron et al. (2019), Experiment 1 was an ideal way to examine the utility of WebGazer for psycholinguistic research.

All analyses were conducted in R (R Core Team, 2021). We followed the common practice of only analyzing looks that were to relevant regions of the display, in this case either the action video or the object video (45% of the total looks in the dataset). This high rate of data loss is due to a combination of factors: Some looks were directed to other areas of the screen; participants sometimes looked away from the screen; and WebGazer sometimes lost track of participants' eye gaze during the experiment. In the analysis, we examined only the looks to the action video, since when only regions of interest are analyzed, any look not to the action video is to the object video.

Results

Test trials: Proportion of looks

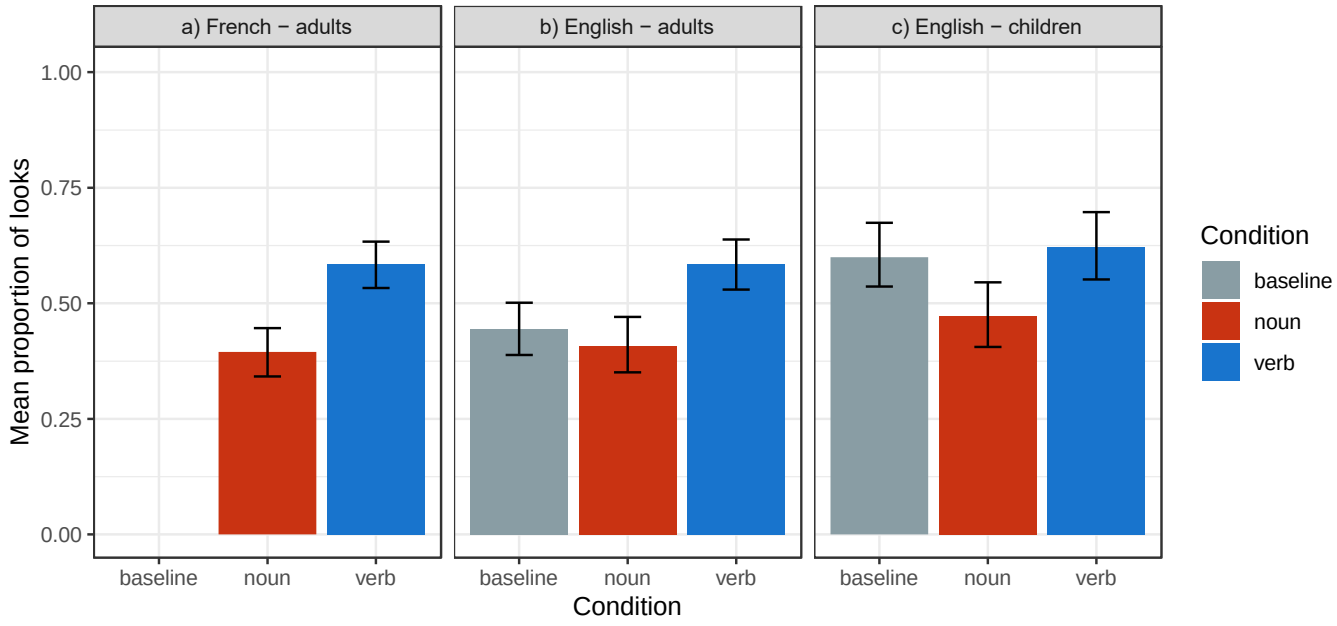
We calculated each participant's proportion of looks to the action video on each test trial and then averaged these three proportions to obtain each participant's mean proportion of looks to the action video across the three test trials. Since participants heard the full target phrase once

before the videos appeared in the event phase, we measured looks from the beginning of the event phase when both images appeared on screen together. Figure 2a shows the overall mean proportion of looks to the action video in each condition, as well as dots representing individual participants' mean proportions of looks. As hypothesized, participants in the verb condition (M = 0.585, SD = 0.171) were more likely to look at the action video than participants in the noun condition (M = 0.395, SD = 0.171).

To test this, we conducted a mixed effects linear regression predicting the arc-sin transformed proportion of looks to the action image during a trial (the same as in the Havron et al. study).[2] The lme4 package was used to conduct the regression analyses (Bates et al., 2015), and the reported p-values were calculated using Satterthwaite's degrees of freedom method via the lmerTest package (Kuznetsova et al., 2017).

[2] Across all three experiments, we also preregistered a mixed effects logistic regression analysis that directly predicted individual looks to the action image. All results agreed between the two types of models, so the details of the logistic regression analyses are not reported here. They can be found in the Supplementary Materials and on GitHub.

Figure 2



Mean overall proportion of looks to the action video or image for a) Experiment 1, b) Experiment 2, and c) Experiment 3. Results are shown for the noun, verb, and (when applicable) baseline conditions during test trials, with bootstrapped confidence intervals. Semi-transparent dots correspond to the mean proportion of looks for individual participants, averaged across the test trials.

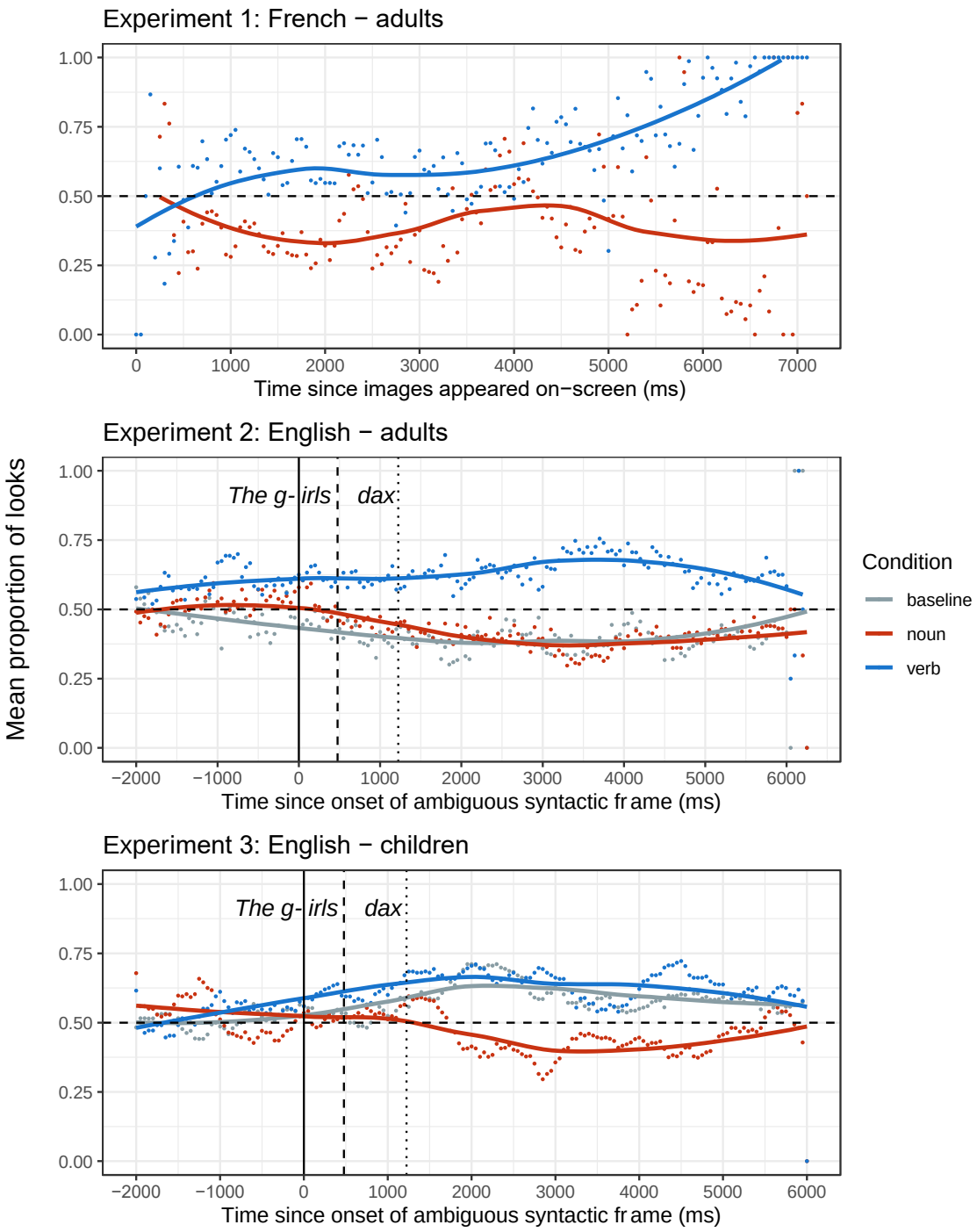
In the mixed effects linear regression, we predicted a participant's arc-sin transformed mean proportion of looks to the action video as a function of condition, with a random by-participant intercept. Condition was centered to avoid high collinearity with the intercept. We did not include a random intercept for item because there were only three test items. There was a significant main effect of condition in the direction expected: Participants in the verb condition were significantly more likely to look at the action video than participants in the noun condition (β = 0.218, SE = 0.048, $p < 0.001$).

Test trials: Time course

While the results relating to proportion of looks demonstrate that adults are indeed using syntactic adaptations to bootstrap novel word meanings, an additional question of interest is how quickly this information can be recruited. Time course data can provide insight into this question. If participants are quickly adjusting their expectations based on the use of the frame *La petite…,* we should see a bias to the action or object video (depending on condition) from the very start of the test trial. Because with the Havron et al. stimuli, participants heard the test trial audio once before the videos appeared on-screen, we do not have information about their eye movements during the first instance of hearing *La petite [novel word]*. However, the time course plot in Figure 3a does suggest that participants in the verb condition looked significantly more at the action video throughout almost the entire event phase of the test trial, and participants in the noun condition consistently looked more at the object video.

In Experiments 2 and 3, we tracked participants' eye movements during the first instance of hearing the syntactic frame of interest on test trials. As we will see, this allowed for more precise analysis of the time course data.

Figure 3



Proportion of looks to the action video or image over time on test trials of Exp. 1 (top), Exp. 2 (middle), and Exp. 3 (bottom). Gray areas represent overall confidence intervals. For Experiments 2 and 3, the zero point (indicated by the vertical black line) corresponds to the onset of the ambiguous syntactic frame (*The g-*); the dashed line represents the mean time point of the end of the syntactic frame, *The girls/girl's…*; and the dotted line indicates the mean end time point of the first utterance of the novel word, such as *The girls/girl's dax*. For Experiment 1, participants heard the full target phrase once before the videos appeared on-screen, so we do not mark these time points.

Training and filler trials

We also analyzed training and filler trials in order to confirm that participants did in fact look at the video described during training trials. This was important to ensure that (a) the eye-tracker reliably measured looks and (b) participants reacted to the descriptions they heard in expected ways. On filler trials, participants should look at the opposite video of their assigned condition. Doing so would indicate their understanding that the narrator could refer to both types of videos, and it was just with the structure *La petite…* that she was biased toward one type of video.

As expected, during training trials, participants in the verb condition looked significantly more to the action video than participants in the noun condition (β = 0.518, *SE* = 0.044, $p <$ 0.001). This pattern was reversed during filler trials (β = -0.433, *SE* = 0.056, $p < 0.001$). More detailed analysis and visualization of training and filler trials, as well as of the exploratory generalization trial[3], is available in the GitHub repository.

Discussion

This study replicated the adult results of Havron et al. (2019), which examined whether syntactic priming influenced word learning. The original study found that participants adapted to a repeated syntactic structure and that they used their updated expectations to interpret an unfamiliar word. Our results were similar: We observed a significant effect of condition in both the mixed effects linear regression model and the mixed effects logistic regression model. That is, compared to participants who heard *La petite (noun)* on training trials, participants who heard *La petite (verb)* looked significantly more at the action video on test trials. Additionally, the time

[3] On the exploratory generalization trial, participants in the verb condition looked significantly more at the action image than participants in the noun condition. More detail is provided in the Supplementary Materials.

course data indicates that this effect remained consistent throughout the trial. This suggests that participants interpreted the ambiguous words on test trials to be consistent with the syntactic structure (noun vs. verb) that had previously been used by the narrator.

The difference we found between conditions appears to be smaller than in the original paper. Havron et al. (2019) reported a mean proportion of looks of 0.653 in the verb condition (compared to our 0.585) and 0.275 in the noun condition (compared to our 0.395); the size of the standard deviations was similar. However, given that this was a replication and that it used online eye-tracking, which is noisier than an in-lab eye-tracking device, this observation is not surprising (Open Science Collaboration, 2015).

It is encouraging that the results of the original paper replicated using the novel method of web-based eye-tracking via WebGazer, where researchers have less direct control over participants' experience during the study. Furthermore, the fact that participants were quite clearly looking at the expected videos during both training and filler trials, when it was obvious which video was being described, validates web-based eye-tracking as a method,[4] despite the somewhat high rate of track loss. Although we found that calibration was sometimes difficult for participants, WebGazer is in the process of becoming more streamlined, and we conclude that it is a useful method for conducting online eye-tracking studies in the future.

However, one limitation of this study design is that there are four training trials but only two filler trials. While this indicates to participants that the speaker *can* talk about both actions and objects, it is still the case that the speaker in the verb condition is overall more likely to talk about actions, and the speaker in the noun condition is overall more likely to talk about objects. In addition, this set-up results in participants being directed to look more frequently at action

[4] That is, in cases where results are averaged across large time windows, as in our proportion of looks analysis. WebGazer is not currently suitable for fine-grained temporal analysis.

(verb condition) or object (noun condition) images during training. We aimed to eliminate this possible confound in Experiment 2.

Experiment 2

Having validated the method via replication of Havron et al. in Experiment 1, we sought to test the main hypothesis – that syntactic adaptation aids in word learning – on English. To this end, we created a version of the study using the English syntactic frame *The girls/The girl's*. Like *La petite,* this frame can be followed by either a noun or a verb (e.g., *The girl's book* vs. *The girls sleep*). The cross-linguistic replication allowed us to test whether the adaptation effect observed in Experiment 1 would generalize to a new syntactic frame in a different language. This would provide evidence for the role of syntactic adaptation as a general mechanism that supports language learning.

A diagram of the trial structure for Experiments 2 and 3 is shown in Figure 4. We made several modifications to the study design that reduced the possible confounds and made it easier to run the study online. The trials used object and action images rather than videos, which simplified the task. In addition, we increased the number of test trials from three to four. We also increased the number of filler trials from two to four in order to match the number of training trials. This ensured that participants in the noun and verb conditions were not biased by looking at more images of the type that matched their condition (action for verb; object for noun) during the training phase. Now, participants were directed to look at equal numbers of action and object images during training trials; the only difference was in the type of linguistic content they heard following the key syntactic frame *The girls/girl's…*. In the noun condition, participants heard

The girl's (noun) on training trials, and in the verb condition, they heard *The girls (verb)* on training trials.

Figure 4

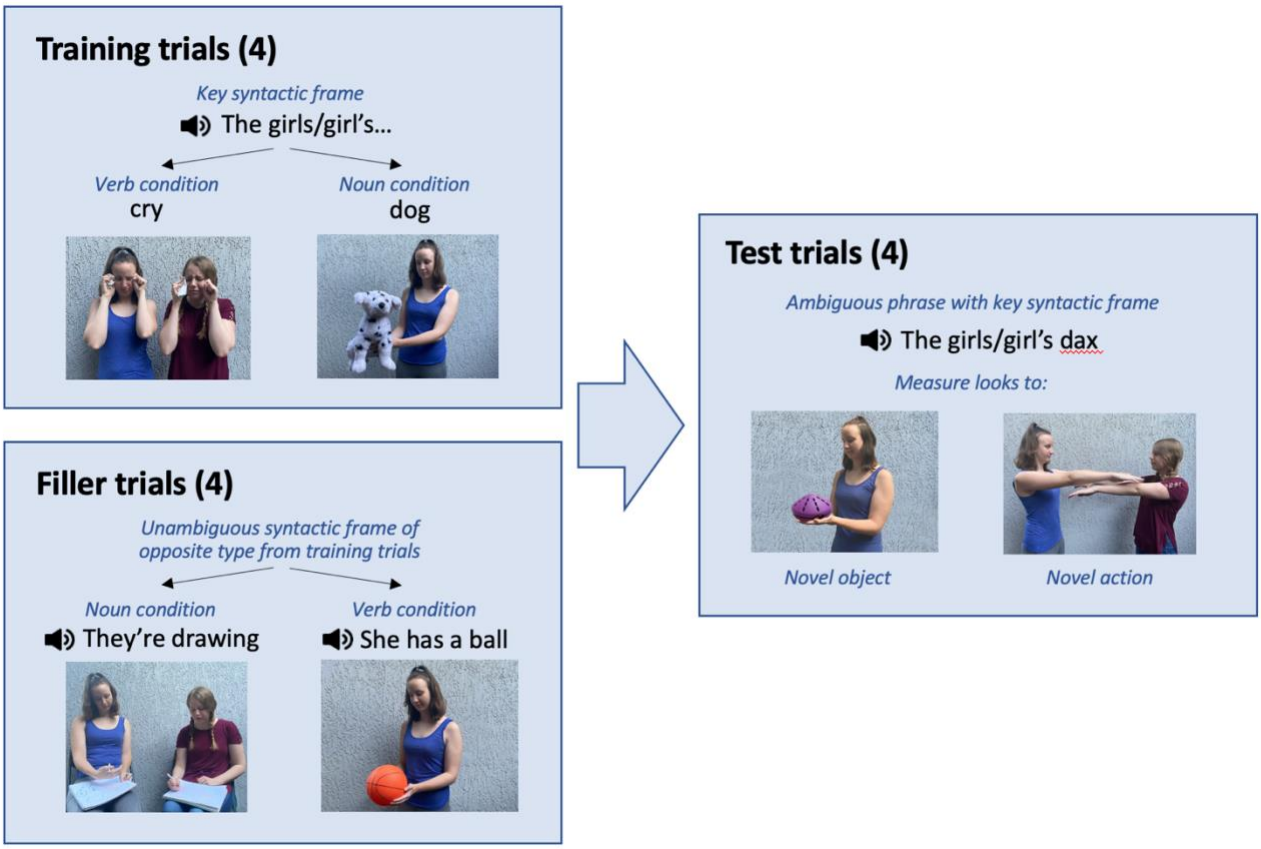


Diagram of experimental set-up for Experiments 2 and 3. Participants saw two training trials, followed by two filler trials, followed by the other two training trials, and then saw all three test trials. The order of the trials within these blocks was randomized.

We also added a baseline condition to the study to examine whether participants would demonstrate bias toward looking at a particular image type even if they did not hear the structure *The girls/Tbe girl's* at all before the test phase. In the baseline condition, participants' training trials included only the filler phrases used in both the noun and verb conditions (*They're Xing* in

the noun condition and *She has an X* in the verb condition). Like the noun and verb conditions, the baseline condition was balanced so that participants would be directed to look at an equal number of action and object images. This was an important step to take to investigate whether the adaptation effect appeared to occur in both the noun and the verb conditions, or whether it was primarily driven by participants in one condition.

On the final trial, we directly asked participants to click on the image they thought the narrator was talking about. This constituted an explicit measure of participants' comprehension of the phrase containing *The girls/The girl's*, in addition to the implicit evidence provided by eye-tracking. We only added the explicit measure on the final trial to avoid potential interference with participants' eye movements.

Methods

Participants

We added an additional baseline condition for Experiment 2 and therefore recruited a larger total of 104 participants (57 female; 41 male; 6 other). Again, we collected data using Prolific and specified that participants had to speak English as their first language. They were randomly assigned to one of the three conditions (35 in the noun condition; 35 in the verb condition; 34 in the baseline condition).

Measures

This study was carried out with WebGazer using the same measures as Experiment 1. Again, we analyzed only looks to the action image or the object image (62% of the total looks in the dataset).

Procedure

Besides the modifications described above, the experiment design was identical to Experiment 1. Trial order was randomized, except that we did not allow more than two training or filler trials in a row. Image sides were counterbalanced.

Results

Proportion of looks

Figure 2b shows the mean proportion of looks to the action image in each condition, with dots representing individual participants' mean proportions of looks. We included only looks after the onset of the ambiguous syntactic frame: *The g-…* in *The girls/girl's….* As in Experiment 1, participants in the verb condition (M = 0.596, SD = 0.193) were more likely to look at the action image than participants in the noun condition (M = 0.389, SD = 0.212). These effects were very similar in size to those observed in Experiment 1. The proportion of looks to the action image in the baseline condition (M = 0.435, SD = 0.187) fell in between the noun and verb condition, but the confidence interval for the baseline condition overlapped with the confidence interval for the verb condition (though not with the noun condition).

For Experiment 2, we compared the noun and verb conditions to the baseline condition. As in Experiment 1, we carried out a mixed effects linear regression which predicted the arc-sin transformed mean proportion of looks to the action image as a function of condition, with a random intercept for participant. In this model and all others for Experiments 2 and 3, condition was dummy-coded using the baseline condition as the reference. There was a significant main effect of condition such that participants in the verb condition looked more to the action image

compared to participants in the baseline condition (β = 0.161, *SE* = 0.053, $p < 0.01$). However, there was not a significant difference between looks to the action image in the noun condition compared to the baseline condition (β = -0.05, *SE* = 0.051, $p = 0.322$).

Time course

To better understand at what time participants recruited their updated expectations, we plotted the time course of the mean proportion of looks to the action image, averaged across the four test trials, in Figure 3b. Specifically, we wished to know whether participants might begin looking at the action or object image even before hearing the full phrase *The girls/girl's [novel word]*. For instance, upon hearing *The g-*, participants could have realized that they were likely about to hear a sentence containing *The girls…* and could have drawn on their updated expectations to look at either the action or object image.

The time course plot reveals several interesting patterns. First, participants in the verb condition appeared more likely to look at the action image for almost the entire duration of the trial, even before hearing the key syntactic frame for the first time (*The girls/girl's [novel word]*). Participants in the baseline condition, on the other hand, were more likely to look at the object image slightly before the naming event occurred and throughout the trial. Finally, participants in the noun condition looked significantly more at the object image than participants in the verb condition, and this effect appeared mostly after hearing the syntactic frame (*The girls/girl's*) for the first time. This pattern of results raises the question of whether participants were making anticipatory looks to the action image in the verb condition, and to the object image in the baseline condition, even before hearing the syntactic frame and the novel word.

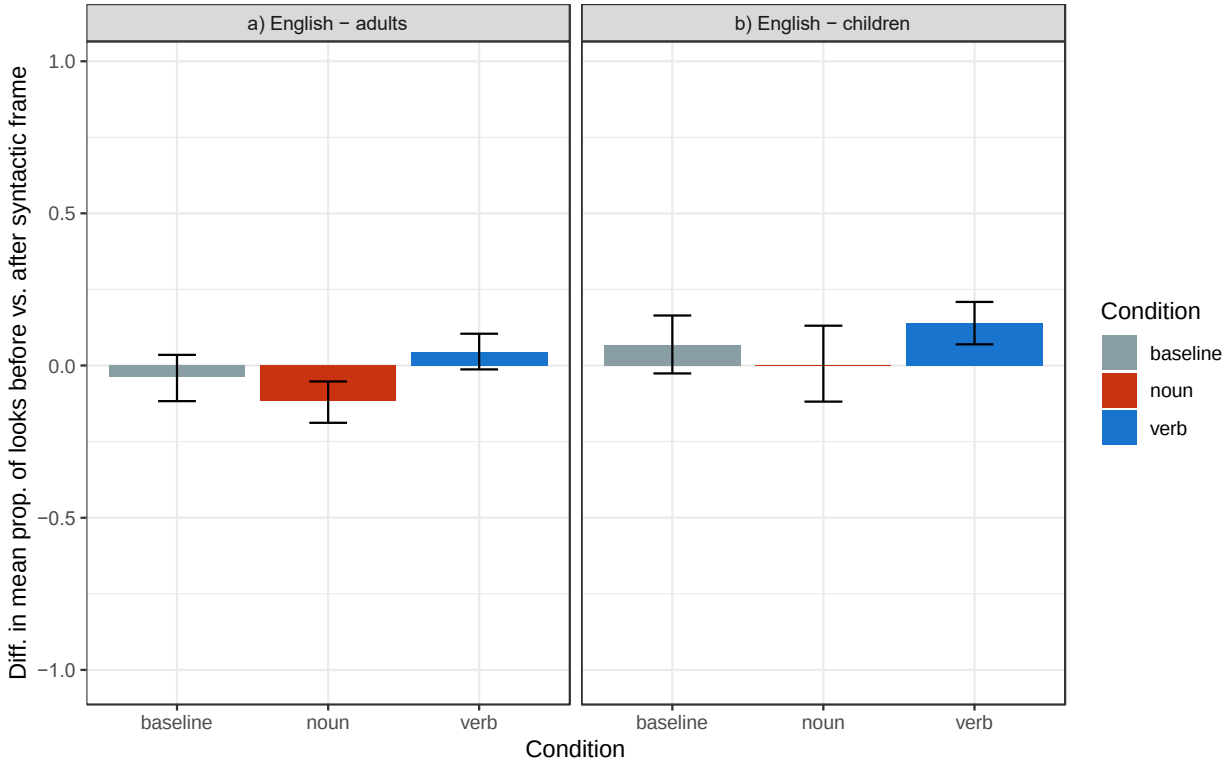
The presence of anticipatory looks might raise the concern that the effects are not driven by interpretation of the sentences, but by something else—for instance, a preference for image type despite the equal number of filler and training trials. To address this, we asked whether there is a detectable change in looks before vs. after the linguistic event of interest: for each trial, we calculated the mean difference in proportion of looks to the action image before the end of the audio *The g-* vs. during the rest of the trial. Figure 5a presents the mean difference in proportion of looks to the action image for each condition, with dots representing trial-level differences in proportions of looks across test trials. Then, we conducted an exploratory mixed effects regression analysis which predicted the difference in proportion of looks to the action image as a function of condition, with a random intercept for participant. There was a marginally significant difference between the difference in proportion of looks for participants in the noun condition vs. the baseline condition (β = -0.087, SE = 0.047, p = 0.068), but no significant difference for participants in the verb condition vs. the baseline condition (β = 0.06, SE = 0.048, p = 0.217).

A likelihood ratio test between this model and a model without the effect of condition did reveal an overall significant main effect of condition, and the confidence intervals for the noun and verb conditions do not overlap. This suggests that there was a difference in proportion of looks to the action image before vs. after the syntactic frame depending on participants' condition.[5] Therefore, while some of the difference in conditions may have been driven by initial image preferences, the time course provides evidence that participants' looking patterns changed as the sentence unfolded. As shown in Figure 5a, this change was in the expected direction, with

[5] In fact, in another exploratory analysis where condition was recoded with the noun condition as the reference, participants in the verb condition had a significantly higher difference in proportion of looks to the action image than did participants in the noun condition (β = 0.147, SE = 0.048, p < 0.01).

participants in the verb condition looking more at the action image and participants in the noun condition looking more at the object image.

Figure 5



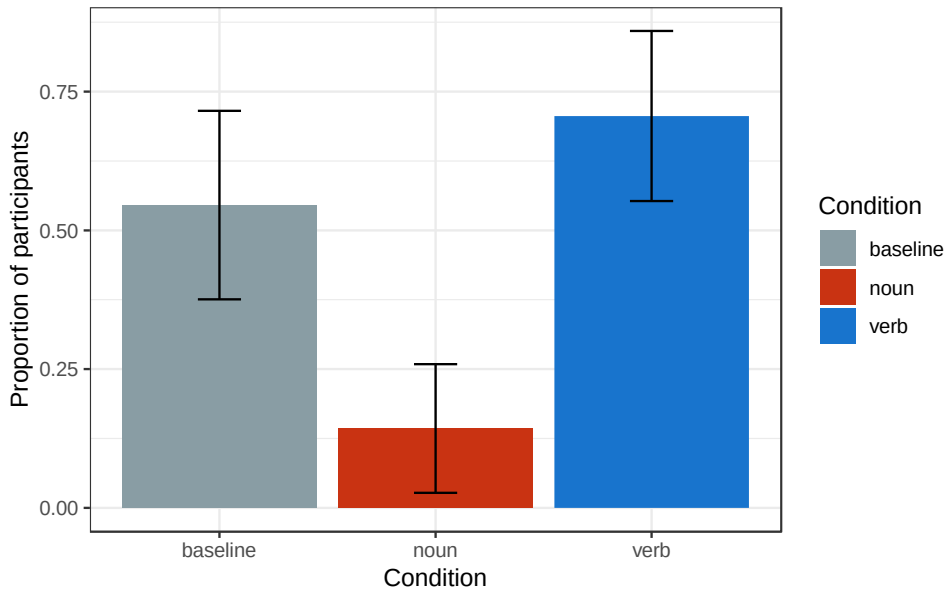
Mean overall difference in proportion of looks to the action image for a) Experiment 2 and b) Experiment 3. The difference is calculated by subtracting the proportion of looks before the end of *The g-* from the proportion of looks after the end of *The g-*. Results are shown for the noun, verb, and baseline conditions during test trials, with bootstrapped confidence intervals. Semi-transparent dots show the distribution of trial-level data points (these are not by-participant averages).

Explicit selection

The final trial of the experiment was identical to other test trials, but once it was completed, we directly asked participants to select the image they thought the narrator had

described. There were large differences by condition, as shown in Figure 6. Participants in the baseline condition were about equally likely to select the action image (54.5%) or the object image (45.5%). In contrast, 85.7% of participants in the noun condition selected the object image, and 70.1% of participants in the verb condition selected the action image. Thus, in their explicit judgments about the meaning of a novel word, participants interpreted the word in line with the examples they had heard during training trials, which were presented in the same syntactic frame.

Figure 6



Proportion of participants in the baseline, noun, and verb conditions who selected the action image when explicitly asked to click on the image they thought the narrator was talking about.

Discussion

The results in the verb and noun conditions of Experiment 2 were similar to those obtained in Experiment 1. Participants' mean proportion of looks to the action image was very similar in the verb (0.585 in Experiment 1 compared to 0.596 in Experiment 2) and noun (0.395 in Experiment 1 compared to 0.389 in Experiment 2) conditions. Again, this effect is not as large as the one observed by Havron et al. (2019), but this may be due to the noisiness of web-based eye-tracking.

Participants' proportion of looks to the action image in the baseline condition fell in between that of the noun and verb conditions. However, based on the 95% confidence interval, which does not include 0.5, baseline participants appeared to show a slight preference for looking at the object image. This could be due to several factors. Participants may have found the object images more interesting, or they may have thought that *The girls/girl's X* was more likely to refer to an object image than an action image. The second explanation is unlikely based on a norming study we conducted before running the experiment. In the norming study, participants heard the audio clips from the test trials (such as *The girls/girl's dax*) unaccompanied by a visual context and were asked, "What does [novel word] describe?" They could then select either "An action" or "An object." Participants performed at chance, indicating that they thought the novel words referred to actions 51% of the time. This suggests that baseline participants were not biased by prosody or by prior expectations about the meanings of the novel words. More likely, they found the object images to be more salient or interesting. We consider this a likely possibility because two norming studies[6] found conflicting results regarding the salience of the object and action images: Participants in one study thought a speaker would be more likely to talk about the object images overall. However, in a follow-up study where images were matched

[6] More details about the procedure and analysis for these studies can be found in the norming section of the GitHub repository.

on salience based on the results from the first study, participants thought a speaker would be more likely to refer to the action images overall. These findings suggest that participants' preferences related to the salience of the images are variable, and it is possible that participants in the baseline condition simply found the object images more interesting than the action images.

Furthermore, the results we obtained using explicit selection on the exploratory trial support the hypothesis that participants in the baseline condition were not drawing inferences about the meanings of the novel words. Participants in the baseline condition performed essentially at chance when asked which image they thought the speaker was referring to, while a large majority (over 70%) of the participants in the noun and verb conditions selected the object image or the action image, respectively. This suggests that participants in the noun and verb conditions updated their expectations about whether the speaker was likely to follow *The girls/girl's* with a noun or a verb, while participants in the baseline condition maintained uncertainty.

The results from explicit selection therefore support the idea that in the baseline condition, the greater number of looks to the object image was likely due to greater salience of those images. In contrast, the time course data suggests that participants in the noun and verb conditions showed differences in their proportion of looks to the action image before vs. after hearing the syntactic frame *The g-*. This supports the idea that participants in the noun and verb conditions were not only showing a preference for a certain type of image. Instead, they appeared to update their looking patterns as the speaker's utterance unfolded and they heard the familiar syntactic frame *The girls/girls'…*

Experiment 3

Methods

In Experiment 3, we extended the paradigm from Experiment 2 to ask whether three- to five-year-old children would show similar patterns of syntactic adaptation during word learning. This would support the idea that adaptation is an important mechanism supporting child language acquisition.

Participants

We collected data through the online Lookit platform (Scott & Schulz, 2017), where children can easily participate in looking time experiments from home. There were 74 participants (42 female; 32 male). Children were assigned to the same three conditions as in Experiment 2 (27 in the noun condition; 23 in the verb condition; 24 in the baseline condition). We preregistered this smaller sample size compared to Experiments 1 and 2 primarily due to the greater difficulty of recruiting children online than recruiting adults. This sample size was similar to that of Havron et al. (2019); in addition, hand-coding children's looks allowed for greater precision than WebGazer did in Experiments 1 and 2, mitigating power concerns resulting from the smaller sample size. Children had to be native English speakers to be eligible for the study.

Measures

Rather than using web-based eye-tracking, which is difficult to use with children, we recorded videos of children through Lookit as they completed the study. The first author hand-coded the children's eye movements as being directed towards the left or right side of the screen. Coding was done blindly, without knowledge of the experimental condition a trial appeared in or which image appeared on which side of the screen.

Procedure

Children either completed the study while sitting on their caregiver's lap, with the caregiver closing their eyes, or while seated on their own. The experiment procedure was nearly identical to Experiment 2, except that the instructions at the beginning of the study were made more child-friendly. We also added attention-getters at the beginning of each trial and took a calibration video of the child looking to the left and right sides of the screen, rather than using a 9-point automatic calibration. The trial structure was the same as in Experiment 2, and we maintained the same modifications to the Havron et al. procedure, implementing an equal number of filler and training trials and using image stimuli rather than videos.

Because a caregiver was not always present with the child, we designed the experiment to run by itself on a computer. As a result, we were not able to pause the experiment and ask children to explicitly select which image they thought the speaker was referring to.

Results

Proportion of looks

The mean proportion of looks to the action image in each condition is shown in Figure 2c. Children in the verb condition (M = 0.629, SD = 0.17) were more likely to look at the action image than children in the noun condition (M = 0.481, SD = 0.187). The proportion of looks to the action image in the baseline condition (M = 0.597, SD = 0.175) fell in between the noun and verb condition. The confidence interval for the baseline condition overlapped with the confidence intervals for both the noun and verb conditions.

We repeated the analyses from Experiment 2: a mixed effects linear regression analysis predicted the arc-sin transformed mean proportion of looks to the action image as a function of condition, with random by-participant intercepts. There was a significant main effect of condition such that children in the noun condition looked less to the action image compared to children in the baseline condition (β = -0.173, *SE* = 0.063, $p < 0.01$). There was not a significant difference in looks between the verb condition and the baseline condition (β = 0.037, *SE* = 0.065, $p = 0.572$).

Time course

The time course of children's looks to the action image over time, averaged across the four test trials, is depicted in Figure 3c.

In contrast to Experiment 2, it appears that in Experiment 3, children in all three conditions showed a slight preference for looking at the action image before hearing the key syntactic frame containing the novel word (e.g., *The girls/girl's dax*). This may have been due to the presence of two people in the action images, which could be more salient for children, compared to the presence of only one person in the object image. However, the time course demonstrates that shortly after the beginning of the ambiguous syntactic frame, *The g-*, children's looking patterns began to diverge. Children in the noun condition looked consistently less at the action image than children in the verb condition. Children in the baseline condition fell in between the two, though they still showed a preference for the action image later on in the trial.

As in Experiment 2, to more precisely determine the point in the trial at which these effects appeared, we calculated the mean difference in each participants' proportion of looks to

the action image before the end of the audio *The g-* vs. during the rest of the trial. The results are illustrated in Figure 5b. We then conducted an exploratory mixed effects regression analysis which predicted the difference in proportion of looks to the action image as a function of condition, with a random intercept for participant. The results showed a significant difference between the change in proportion of looks for participants in the noun condition compared to participants in the baseline condition (β = -0.165, *SE* = 0.068, *p* = 0.017). There was no significant difference between participants in the verb condition and those in the baseline condition (β = 0.022, *SE* = 0.07, *p* = 0.757). This suggests that for children in the noun condition, who appeared to drive the effects in the results, there were changes in their eye movements over the course of the trial. As in Experiment 2, this provides evidence that children's looking preferences were updated as they recognized the familiar syntactic frame.

General Discussion

The three experiments reported here investigated whether syntactic adaptation is a mechanism implicated in word learning, as suggested by Havron et al. (2019). Experiment 1 was a direct replication of Havron et al. (2019) with French speaking adults. Experiment 2 was a cross-linguistic replication with English speaking adults and a novel syntactic frame. Experiment 3 was identical to Experiment 2, but with three- to five-year-old English speaking children. All three experiments provided evidence that participants adapted to the usage of the syntactic frame they encountered. In the English experiments, participants in the noun condition had a stronger expectation that the speaker would use *The girl's [noun]*, and participants in the verb condition had a stronger expectation that the speaker would use *The girls [verb]*, guiding the interpretation of an ambiguous novel word presented in the same syntactic frame, such as *The girls/girl's dax.*

This was reflected by participants in the verb condition exhibiting a preference for looking at the action image over the object image on test trials, and vice versa in the noun condition (though this effect was weaker in children than adults).

Across experiments, the baseline condition also demonstrated variable results: English-speaking adults in the baseline condition appeared to show a preference for the object image, while English-speaking children in the baseline condition appeared to show a preference for the action image. However, participants in the baseline condition always showed a proportion of looks to the action image that fell in between the noun and verb conditions, as we would expect. In addition, the explicit selection task in Experiment 2 provided evidence that baseline condition participants were not forming interpretations about the meanings of the ambiguous novel words.

For both children and adults, exploratory time course analysis suggested that depending on participants' condition, there were differences in their looking patterns, in the directions expected, as the trial unfolded. Similar to the main proportion of looks analysis, these effects appeared to be driven by participants in the verb condition for adults (though the comparison with the baseline condition did not reach significance) and by participants in the noun condition for children. Nonetheless, since Webgazer is not currently suitable for fine-grained temporal analysis, other methods are likely needed to shed more light upon the question of exactly when in the syntactic frame children and adults begin using their updated expectations to guide their interpretations.

These results are similar to the key findings of Havron et al. (2019). In the original study, researchers found a larger adaptation effect for children in the verb condition, who were exposed to a less frequent syntactic structure in French than children in the noun condition. In the same way, the noun structure we used is more frequent than the verb structure in English; there are

2,125 instances of *The girl's [noun]* in the Corpus of Contemporary American English (Davies, 2008), compared to 1,013 instances of *The girls [verb]*. Furthermore, English speakers often use the structure *The girls are [verb]ing* rather than *The girls [verb],* while there is not a common alternative to *The girl's [noun].* As a result, the verb structure may have seemed more unusual to children in the verb condition than the noun structure did to children in the noun condition. The more surprising structure could lead to a stronger adaptation effect for children in the verb condition. This would align with Jaeger & Snider's (2013) finding that the strength of syntactic priming is affected by the prime's prediction error. Moreover, we ensured that participants were not biased toward the verb interpretation based on factors such as prosody by running a norming experiment beforehand where we played only the audio clips (such as *The girls/girl's dax*) and asked participants whether they thought *dax* was an action or an object. Participants judged that the novel words referred to actions 51.1% of the time, suggesting that the verb and noun interpretations were about equally plausible. Thus, the more consistent adaptation effect in the verb condition does not simply appear to be due to a baseline bias toward the verb interpretation; it more likely represents stronger syntactic adaptation to the more surprising structure.

Although participants in the verb condition exhibited a higher proportion of looks to the action image than participants in the noun condition across all three experiments, participants in the baseline condition showed varying results in Experiments 2 and 3. In Experiment 2, the English-speaking adults in the baseline condition slightly preferred looking at the object image, while in Experiment 3, the English-speaking children in the baseline condition preferred looking at the action image. The explicit selection results from Experiment 2 suggest that adults in the baseline condition were not drawing inferences about the meaning of the novel word and that this effect was more likely due to participants finding the object image more salient. We were

not able to ask the children in Experiment 3 to explicitly select the action or object image, but we suspect that salience also guided baseline children's looking preferences because the norming studies discussed in Experiment 2 also showed variable results in how salient the images were, and because children in the baseline condition showed the opposite pattern of looks (with a preference for the action image) than adults in the baseline condition (who slightly preferred the object image). Further studies, with greater numbers of participants, would be needed to examine baseline preferences for looking at action images vs. object images and to determine in which direction, if not both, participants engage in adaptation.

Despite the variation in the baseline results, we observed across all three experiments that participants in the verb condition looked more to the action image than participants in the noun condition. This replicated the key result of Havron et al. (2019) both directly and cross-linguistically in English, with children and adults. An important contribution we added to build on Havron et al.'s work was the equal number of filler trials and training trials in Experiments 2 and 3. This ensured that participants heard the speaker refer to action and object images with equal frequency; it was only with the specific structure *The girls/girl's…* that participants developed an expectation about whether the speaker would use a noun or a verb. Thus, we can be confident that our results reflect adaptation to the usage of a particular linguistic structure and not to the speaker's general likelihood to talk about actions or objects. This adaptation then guided participants' interpretations of an ambiguous novel word that was presented in the same syntactic frame.

Another unique contribution of these experiments is that they demonstrate the feasibility of conducting eye-tracking studies through web-based platforms. Both WebGazer and Lookit are relatively new tools in the research community and are still undergoing development and

expansion. However, both platforms have enormous potential in allowing eye-tracking studies—which have historically not been possible to conduct outside of research labs—to be carried out with larger and more diverse populations (Gosling et al., 2010). The fact that we replicated the findings of Havron et al. (2019) directly and cross-linguistically suggests that conducting studies on these platforms is viable for experiments such as this one, where looking time is computed over a large analysis window.

Overall, these results support and extend those of Havron et al. (2019). The similar findings across French and English, and between children and adults, lend support to the proposal that syntactic adaptation may be an important mechanism for guiding language acquisition. Future work should investigate adults' and children's baseline preferences relating to factors such as image salience and structure frequency, as well as how these preferences interact with new statistical information about a speaker's usage of syntax. Additional studies that carefully tease apart these factors will contribute to a formal model of expectation update during syntactic adaptation.

Future work should also further examine the specificity of syntactic adaptation in word-learning contexts. For instance, since we used the same speaker throughout the experiment, it remains an open question whether this adaptation effect is speaker-specific or whether it could generalize to other speakers. In addition, future studies could vary the particular lexical content used within the syntactic structure (e.g., *The boys/boy's X*) to determine whether participants generalize their expectations about the underlying syntactic structure to a slightly different phrase. If children are likely to encounter repeated syntax in short bursts within specific contexts, as in the example where a caregiver utters similar phrases such as *The dog is running, The dog is playing,* etc., then we might expect syntactic adaptation to be relatively specific to the speaker

and the lexical content. Questions also remain about how syntactic adaptation may take place in naturalistic contexts, where children are likely to repeat or respond to novel words that they hear (Clark, 2007). During language acquisition, syntactic adaptation is likely to be one of many tools that children can draw upon—along with speaker cues, prior knowledge, visual context, and more—as they rapidly learn new words.

While the role of syntactic adaptation in word learning merits further investigation, these three experiments suggest that children and adults are able to not only flexibly update their expectations about a speaker's syntactic preferences, but also draw on these expectations to guide novel word learning.

References

Arciuli, J., & Simpson, I. C. (2011). Statistical learning in typically developing children: The role of age and speed of stimulus presentation. *Developmental Science*, *14*(3), 464–473. https://doi.org/10.1111/j.1467-7687.2009.00937.x

Arnon, I. (2019). Statistical Learning, Implicit Learning, and First Language Acquisition: A Critical Evaluation of Two Developmental Predictions. *Topics in Cognitive Science*, tops.12428. https://doi.org/10.1111/tops.12428

Balcan, M. F., & Feldman, V. (2014). Statistical Active Learning Algorithms for Noise Tolerance and Differential Privacy. *ArXiv:1307.3102 [Cs, Stat]*. http://arxiv.org/abs/1307.3102

Bates, D., Mächler, M., Bolker, B., & Walker, S. (2015). Fitting Linear Mixed-Effects Models Using lme4. *Journal of Statistical Software*, *67*(1). https://doi.org/10.18637/jss.v067.i01

Bencini, G., & Valian, V. (2008). Abstract sentence representations in 3-year-olds: Evidence from language production and comprehension. *Journal of Memory and Language*, *59*, 97–113. https://doi.org/10.1016/j.jml.2007.12.007

Bernal, S., Lidz, J., Millotte, S., & Christophe, A. (2007). Syntax Constrains the Acquisition of Verb Meaning. *Language Learning and Development*, *3*, 325–341. https://doi.org/10.1080/15475440701542609

Bernolet, S., & Hartsuiker, R. J. (2010). Does verb bias modulate syntactic priming? *Cognition*, *114*(3), 455–461. https://doi.org/10.1016/j.cognition.2009.11.005

Bock, J. K. (1986). Syntactic persistence in language production. *Cognitive Psychology*, *18*(3), 355–387. https://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*(2), 177–192. https://doi.org/10.1037/0096-3445.129.2.177

Boyland, J. T., & R. Anderson, J. (1998). Evidence that Syntactic Priming is Long Lasting. *Proceedings Ofthe Twentieth Annual Conference Ofthe Cognitive Science Society*, 1205. https://doi.org/10.1184/R1/6614720.v1

Bradlow, A. R., & Bent, T. (2008). Perceptual adaptation to non-native speech. *Cognition*, *106*(2), 707–729. https://doi.org/10.1016/j.cognition.2007.04.005

Branigan, H. P., & Messenger, K. (2016). Consistent and cumulative effects of syntactic experience in children's sentence production: Evidence for error-based implicit learning. *Cognition*, *157*, 250–256. https://doi.org/10.1016/j.cognition.2016.09.004

Branigan, H. P., Pickering, M. J., & Cleland, A. A. (2000). Syntactic co-ordination in dialogue. *Cognition*, *75*(2), B13–B25. https://doi.org/10.1016/S0010-0277(99)00081-5

Branigan, H. P., Pickering, M. J., McLean, J. F., & Cleland, A. A. (2007). Syntactic alignment and participant role in dialogue. *Cognition*, *104*(2), 163–197. https://doi.org/10.1016/j.cognition.2006.05.006

Brooks, P. J., & Tomasello, M. (1999). Young children learn to produce passives with nonce verbs. *Developmental Psychology*, *35*(1), 29–44. https://doi.org/10.1037/0012-1649.35.1.29

Chang, F., Dell, G. S., & Bock, K. (2006). Becoming syntactic. *Psychological Review*, *113*(2), 234–272. https://doi.org/10.1037/0033-295X.113.2.234

Christophe, A., Dautriche, I., de Carvalho, A., & Brusini, P. (2016, December 1). *Bootstrapping the Syntactic Bootstrapper*.

Clark, E. V. (2007). Young children's uptake of new words in conversation. *Language in Society*, *36*(2), 157–182. https://doi.org/10.1017/S0047404507070091

Cleland, A. A., & Pickering, M. J. (2003). The use of lexical and syntactic information in language production: Evidence from the priming of noun-phrase structure. *Journal of Memory and Language*, *49*(2), 214–230. https://doi.org/10.1016/S0749-596X(03)00060-3

Dautriche, I., Swingley, D., & Christophe, A. (2015). Learning novel phonological neighbors: Syntactic category matters. *Cognition*, *143*, 77–86. https://doi.org/10.1016/j.cognition.2015.06.003

Davies, M. (2008). *The Corpus of Contemporary American English (COCA). Available online at https://www.english-corpora.org/coca/.*

Denison, S., & Xu, F. (2019). Infant Statisticians: The Origins of Reasoning Under Uncertainty. *Perspectives on Psychological Science*, *14*(4), 499–509. https://doi.org/10.1177/1745691619847201

Fine, A. B., & Jaeger, T. F. (2013). Evidence for Implicit Learning in Syntactic Comprehension. *Cognitive Science*, *37*(3), 578–591. https://doi.org/10.1111/cogs.12022

Fine, A. B., & Jaeger, T. F. (2016). The role of verb repetition in cumulative structural priming in comprehension. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *42*(9), 1362–1376. https://doi.org/10.1037/xlm0000236

Fine, A. B., Jaeger, T. F., Farmer, T. A., & Qian, T. (2013). Rapid Expectation Adaptation during Syntactic Comprehension. *PLOS ONE*, *8*(10), e77661. https://doi.org/10.1371/journal.pone.0077661

Gambi, C., Pickering, M., & Rabagliati, H. (2016). Beyond associations: Sensitivity to structure in pre-schoolers' linguistic predictions. *Cognition*, *157*, 340–351. https://doi.org/10.1016/j.cognition.2016.10.003

Gleitman, L. (1990). The structural sources of verb meanings. *Language Acquisition: A Journal of Developmental Linguistics*, *1*(1), 3–55. https://doi.org/10.1207/s15327817la0101_2

Gopnik, A., & Bonawitz, E. (2015). Bayesian models of child development. *WIREs Cognitive Science*, *6*(2), 75–86. https://doi.org/10.1002/wcs.1330

Gosling, S. D., Sandy, C. J., John, O. P., & Potter, J. (2010). Wired but not WEIRD: The promise of the Internet in reaching more diverse samples. *Behavioral and Brain Sciences*, *33*(2–3), 94–95. https://doi.org/10.1017/S0140525X10000300

Gries, S. Th. (2005). Syntactic Priming: A Corpus-based Approach. *Journal of Psycholinguistic Research*, *34*(4), 365–399. https://doi.org/10.1007/s10936-005-6139-3

Harrington Stack, C. M., James, A. N., & Watson, D. G. (2018). A failure to replicate rapid syntactic adaptation in comprehension. *Memory & Cognition*, *46*(6), 864–877. https://doi.org/10.3758/s13421-018-0808-6

He, A. X., & Lidz, J. (2017). Verb Learning in 14- and 18-Month-Old English-Learning Infants. *Language Learning and Development*, *13*(3), 335–356. https://doi.org/10.1080/15475441.2017.1285238

Huang, Y. T., & Arnold, A. R. (2016). Word learning in linguistic context: Processing and memory effects. *Cognition*, *156*, 71–87. https://doi.org/10.1016/j.cognition.2016.07.012

Huttenlocher, J., Vasilyeva, M., & Shimpi, P. (2004). Syntactic priming in young children. *Journal of Memory and Language*, *50*(2), 182–195. https://doi.org/10.1016/j.jml.2003.09.003

Jaeger, T. F., & Snider, N. E. (2013). Alignment as a consequence of expectation adaptation: Syntactic priming is affected by the prime's prediction error given both prior and recent experience. *Cognition*, *127*(1), 57–83. https://doi.org/10.1016/j.cognition.2012.10.013

Kamide, Y. (2012). Learning individual talkers' structural preferences. *Cognition*, *124*(1), 66–71. https://doi.org/10.1016/j.cognition.2012.03.001

Kaschak, M. P. (2007). Long-term structural priming affects subsequent patterns of language production. *Memory & Cognition*, *35*(5), 925–937. https://doi.org/10.3758/BF03193466

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*(2), 148–203. https://doi.org/10.1037/a0038695

Kleinschmidt, D., Fine, A., & Jaeger, T. F. (2012, January 1). *A belief-updating model of adaptation and cue combination in syntactic comprehension*. Proceedings of the 34rd Annual Meeting of the Cognitive Science Society (CogSci12).

Kraljic, T., & Samuel, A. G. (2007). Perceptual adjustments to multiple speakers. *Journal of Memory and Language*, *56*(1), 1–15. https://doi.org/10.1016/j.jml.2006.07.010

Kroczek, L. O. H., & Gunter, T. C. (2017). Communicative predictions can overrule linguistic priors. *Scientific Reports*, *7*(1), 17581. https://doi.org/10.1038/s41598-017-17907-9

Krogh, L., Vlach, H., & Johnson, S. (2013). Statistical Learning Across Development: Flexible Yet Constrained. *Frontiers in Psychology*, *3*. https://www.frontiersin.org/article/10.3389/fpsyg.2012.00598

Kuznetsova, A., Brockhoff, P. B., & Christensen, R. H. B. (2017). lmerTest Package: Tests in Linear Mixed Effects Models. *Journal of Statistical Software*, *82*(13). https://doi.org/10.18637/jss.v082.i13

Ledoux, K., Traxler, M., & Swaab, T. (2007). Syntactic Priming in Comprehension Evidence From Event-Related Potentials. *Psychological Science*, *18*, 135–143. https://doi.org/10.1111/j.1467-9280.2007.01863.x

Liu, L., Burchill, Z., Tanenhaus, M. K., & Jaeger, T. F. (2017). Failure to replicate talker-specific syntactic adaptation. *Proceedings of the 39th Annual Meeting of the Cognitive Science Society*, 2616–2621.

Long, D. L., & Prat, C. S. (2008). Individual differences in syntactic ambiguity resolution: Readers vary in their use of plausibility information. *Memory & Cognition*, *36*(2), 375–391. https://doi.org/10.3758/MC.36.2.375

Lu, J., Lassiter, D., & Degen, J. (2021, July 28). *Syntactic satiation is driven by speaker-specific adaptation*.

Mcmurray, B., Aslin, R., & Toscano, J. (2009). Statistical learning of phonetic categories: Insights from a computational approach. *Developmental Science*, *12*, 369–378. https://doi.org/10.1111/j.1467-7687.2009.00822.x

Messenger, K., Branigan, H., & McLean, J. (2011). Evidence for (shared) abstract structure underlying children's short and full passives. *Cognition*, *121*, 268–274. https://doi.org/10.1016/j.cognition.2011.07.003

Noppeney, U., & Price, C. (2004). An FMRI study of syntactic adaptation. *Journal of Cognitive Neuroscience*, *16*, 702–713. https://doi.org/10.1162/089892904323057399

Open Science Collaboration. (2015). *Estimating the reproducibility of psychological science*. https://www.science.org/doi/10.1126/science.aac4716

Ostrand, R., & Ferreira, V. S. (2019). Repeat after us: Syntactic alignment is not partner-specific. *Journal of Memory and Language*, *108*, 104037. https://doi.org/10.1016/j.jml.2019.104037

Papoutsaki, A., Sangkloy, P., Laskey, J., Daskalova, N., Huang, J., & Hays, J. (2016). WebGazer: Scalable Webcam Eye Tracking Using User Interactions. *Proceedings of the 25th International Joint Conference on Artificial Intelligence (IJCAI)*, 3839–3845.

Peter, M., Chang, F., Pine, J., Blything, R., & Rowland, C. (2015). When and how do children develop knowledge of verb argument structure? Evidence from verb bias effects in a structural priming task. *Journal of Memory and Language*, *81*, 1–15. https://doi.org/10.1016/j.jml.2014.12.002

Pickering, M. J., & Ferreira, V. S. (2008). Structural priming: A critical review. *Psychological Bulletin*, *134*(3), 427–459. https://doi.org/10.1037/0033-2909.134.3.427

Pickering, M. J., & Garrod, S. (2004). Toward a Mechanistic Psychology of Dialogue. *Behavioral and Brain Sciences*, *27*(2), 169–190. https://doi.org/10.1017/S0140525X04000056

Prasad, G., & Linzen, T. (2021). Rapid syntactic adaptation in self-paced reading: Detectable, but only with many participants. *Journal of Experimental Psychology. Learning, Memory, and Cognition*, *47*(7), 1156–1172. https://doi.org/10.1037/xlm0001046

R Core Team. (2021). *R: A language and environment for statistical computing.* https://www.R-project.org/

Raz, G., & Saxe, R. (2020). Learning in Infancy Is Active, Endogenously Motivated, and Depends on the Prefrontal Cortices. *Annual Review of Developmental Psychology*, *2*(1), 247–268. https://doi.org/10.1146/annurev-devpsych-121318-084841

Romberg, A. R., & Saffran, J. R. (2010). Statistical learning and language acquisition. *WIREs Cognitive Science*, *1*(6), 906–914. https://doi.org/10.1002/wcs.78

Rowland, C. F., Chang, F., Ambridge, B., Pine, J. M., & Lieven, E. V. M. (2012). The development of abstract syntax: Evidence from structural priming and the lexical boost. *Cognition*, *125*(1), 49–63. https://doi.org/10.1016/j.cognition.2012.06.008

Ryskin, R., Kurumada, C., & Brown-Schmidt, S. (2019). Information Integration in Modulation of Pragmatic Inferences During Online Language Comprehension. *Cognitive Science*, *43*(8), e12769. https://doi.org/10.1111/cogs.12769

Saffran, J., & Kirkham, N. (2017). Infant Statistical Learning. *Annual Review of Psychology*, *69*, 1–23. https://doi.org/10.1146/annurev-psych-122216-011805

Saffran, J. R., Aslin, R. N., & Newport, E. L. (1996). Statistical learning by 8-month-old infants. *Science (New York, N.Y.)*, *274*(5294), 1926–1928. https://doi.org/10.1126/science.274.5294.1926

Schulz, L. (2012). The origins of inquiry: Inductive inference and exploration in early childhood. *Trends in Cognitive Sciences*, *16*(7), 382–389. https://doi.org/10.1016/j.tics.2012.06.004

Schuster, S., & Degen, J. (2020). I know what you're probably going to say: Listener adaptation to variable use of uncertainty expressions. *Cognition*, *203*, 104285. https://doi.org/10.1016/j.cognition.2020.104285

Scott, K., & Schulz, L. (2017). Lookit (Part 1): A New Online Platform for Developmental Research. *Open Mind*. https://doi.org/10.1162/OPMI_a_00002

Segaert, K., Kempen, G., Petersson, K. M., & Hagoort, P. (2013). Syntactic priming and the lexical boost effect during sentence production and sentence comprehension: An fMRI study. *Brain and Language*, *124*, 174–183. https://doi.org/10.1016/j.bandl.2012.12.003

Shimpi, P. M., Gámez, P. B., Huttenlocher, J., & Vasilyeva, M. (2007). Syntactic priming in 3- and 4-year-old children: Evidence for abstract representations of transitive and dative forms. *Developmental Psychology*, *43*(6), 1334–1346. https://doi.org/10.1037/0012-1649.43.6.1334

Shufaniya, A., & Arnon, I. (2018). Statistical Learning Is Not Age-Invariant During Childhood: Performance Improves With Age Across Modality. *Cognitive Science*, *42*(8), 3100–3115. https://doi.org/10.1111/cogs.12692

Thothathiri, M., & Snedeker, J. (2008). Syntactic priming during language comprehension in three- and four-year-old children. *Journal of Memory and Language*, *58*(2), 188–213. https://doi.org/10.1016/j.jml.2007.06.012

Vallabha, G. K., McClelland, J. L., Pons, F., Werker, J. F., & Amano, S. (2007). Unsupervised learning of vowel categories from infant-directed speech. *Proceedings of the National Academy of Sciences*, *104*(33), 13273–13278. https://doi.org/10.1073/pnas.0705369104

Waxman, S. R., Lidz, J. L., Braun, I. E., & Lavin, T. (2009). Twenty four-month-old infants' interpretations of novel verbs and nouns in dynamic scenes. *Cognitive Psychology*, *59*(1), 67–95. https://doi.org/10.1016/j.cogpsych.2009.02.001

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*(2), 250–271. https://doi.org/10.1016/j.cogpsych.2008.08.002

Xu, F. (2019). Towards a rational constructivist theory of cognitive development. *Psychological Review*, *126*(6), 841–864. https://doi.org/10.1037/rev0000153

Xu, F., & Tenenbaum, J. B. (2007). Word learning as Bayesian inference. *Psychological Review*, *114*(2), 245–272. https://doi.org/10.1037/0033-295X.114.2.245

Yildirim, I., Degen, J., Tanenhaus, M. K., & Jaeger, T. F. (2016). Talker-specificity and adaptation in quantifier interpretation. *Journal of Memory and Language*, *87*, 128–143. https://doi.org/10.1016/j.jml.2015.08.003

Yuan, S., & Fisher, C. (2009). "Really? She blicked the baby?": two-year-olds learn combinatorial facts about verbs by listening. *Psychological Science*, *20*(5), 619–626. https://doi.org/10.1111/j.1467-9280.2009.02341.x