Syntactic adaptation and word learning in children and adults

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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 toward using either familiar verbs or familiar nouns in a syntactic context which permitted both structures. This prime later 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 the 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. 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.

Keywords: syntactic priming; adaptation; word learning; language acquisition

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Introduction

How do children learn language so quickly? In just a few years, children can learn how to segment a continuous speech stream into words and phrases and map this linguistic content to its meaning. One source that children may draw on when learning unfamiliar words is morphosyntactic information. Specifically, syntactic bootstrapping has been proposed as a process by which children can infer the meanings of unfamiliar words partially based on their morphosyntactic 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* is a verb and therefore likely refers to an action. In this case, the *-ing* affix is a relatively stable and reliable cue to the novel word's part of speech. However, language is highly variable across speakers and situations. To cope with such variability, one mechanism listeners can rely on is linguistic adaptation: the ability to track patterns in the speech of others and update their expectations based on these patterns. Adaptation, including adaptation to a speaker's choice of syntactic structure, is well-studied in adults (Bradlow & Bent, 2008; Chang et al., 2006; Fine et al., 2013; Kleinschmidt & Jaeger, 2015; Kraljic & Samuel, 2007; Ostrand & Ferreira, 2019; Prasad & Linzen, 2021; Ryskin et al., 2019; Schuster & Degen, 2020; Yildirim et al., 2016). Do children also exhibit evidence of syntactic adaptation? And can they use expectations updated during syntactic adaptation to bootstrap word learning?

Havron, de Carvalho, Fiévet, & Christophe (2019) investigated children's capacity to infer novel word meanings by adapting to specific syntactic structures, showing that French-speaking adults and children demonstrated 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 prior work examining both syntactic priming and syntactic bootstrapping.

Syntactic Priming in Adults

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 (Bock, 1986; Branigan et al., 2000, 2007; Cleland & Pickering, 2003; Ostrand & Ferreira, 2019; Pickering & Garrod, 2004) and demonstrating facilitated comprehension of utterances that contain the structure (Fine et al., 2013; Fine & Jaeger, 2013; Kamide, 2012; Lu et al., 2021; Prasad & Linzen, 2021). On the production side, experimental studies have long shown that participants tend to align their syntactic structures in dialogue (Bock, 1986). 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), indicating that syntactic alignment is not merely a product of experimental settings but also a characteristic of natural communication.

In addition, syntactic priming effects have increasingly been investigated in comprehension (Pickering & Ferreira, 2008). One study used a self-paced reading paradigm to examine participants' comprehension of garden path sentences (Fine et al., 2013). 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). Syntactic priming 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). Similarly, syntactic 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).

Several studies have suggested that syntactic priming involves not just transient activation of representations, but can also have long-term, cumulative effects. An experiment that used a similar picture task as Bock (1986) to elicit sentences containing dative verbs found that syntactic priming still occurred when there was a 20-minute delay between the priming stage and participants' productions (Boyland & Anderson (1998). 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).

While syntactic priming has sometimes been attributed to short-lived activation of representations (Branigan et al., 2000; Pickering & Branigan, 1998; Pickering & Garrod, 2004), the findings of cumulative and long-term priming effects lend support to an explanation of syntactic priming effects as a form of adaptation that is linked to implicit learning about the distributions of sentence structures (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 (Havron et al., 2020). Differential adaptation depending on a cue's reliability has been found in both adults and

four- to five-year-old children (Beretti et al., 2020; Yurovsky et al., 2017). 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). Thus, although the exact mechanism remains disputed, syntactic alignment (in production) and syntactic priming (in comprehension) have been clearly demonstrated in adults.

Syntactic Priming in Children

Syntactic priming has the potential to act as a powerful support for children's language acquisition. A number of studies have shown that infants and children are able to engage in statistical learning, meaning that they can extract statistical regularities from an input (Arciuli & Simpson, 2011; Arnon, 2019; Krogh et al., 2013; Saffran et al., 1996; Saffran & Kirkham, 2017; Shufaniya & Arnon, 2018). In the auditory domain, statistical learning appears to develop very early on, from at least the age of 8 months, leading many to suggest that it plays an important role in early language learning (Arciuli & Torkildsen, 2012; Raviv & Arnon, 2018; Romberg & Saffran, 2010). With regard to syntax, in particular, 1-year-old infants have been found to be able to extract grammatical information from statistical regularities in an artificial language after less than two minutes of exposure (Gomez & Gerken, 1999). 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). For instance, 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 (Peter et al., 2015). 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. 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 priming 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 priming 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. Cumulative syntactic priming has also been shown over the course of a single session, for the interpretation of ambiguous sentences, with a larger effect in five- to six-year-old children than in adults (Havron et al., 2020). Relatedly, the magnitude of the priming effect has been found to be larger for young children than for older children and adults (Rowland et al., 2012). These results suggest that, at least in some contexts, children may have expectations about sentence structure that are more uncertain or more flexibly updated than adults' expectations. A 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.

The connection between acquisition and an adaptation account of syntactic priming 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. The 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). On the other hand, one study did not find evidence of an immediate prime surprisal effect in children, while it did in adults, raising questions about whether children are truly engaging in error-based learning (Fazekas et al., 2020). Both groups did, however, show syntactic priming effects on production, and more surprising input was associated with stronger priming overall.

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. Such a 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).

Syntactic Bootstrapping and Word Learning

The syntactic bootstrapping literature provides further motivation for the idea that syntactic information is recruited during word learning. Knowledge of a small number of syntactic cues could prove immensely helpful in constraining children's hypotheses about the meaning of a novel word, such as inferring that *dax* in *It's daxing*

is a verb that refers to an action (Brown, 1957; Gleitman, 1990; Waxman, 1999).

Experimental evidence indicates that children are able to draw on syntax during word learning from an early age. Upon hearing *This one is a blicket,* infants as young as 14 months infer that *blicket* refers to an object and not an object property; they make no such inference for *This one is blickish* (Booth & Waxman, 2003). 24-month-olds 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). Using eye-tracking paradigms, 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. At a broader level, children who are more sensitive to syntactic cues in general have been found to have more accurate interpretations of novel words (Huang & Arnold, 2016).

Much work on syntactic bootstrapping has examined children's ability to use verb arguments to guide their interpretations of verbs (Gleitman et al., 2005). Specifically, a structure-mapping account of verb learning proposes that children have a universal bias to map each noun phrase in a sentence onto a participant role in an event (Fisher, 1994; Fisher et al., 2020; Naigles, 1990). For instance, 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, indicating that they used syntactic cues (i.e., presence of a direct object in transitive sentences) to interpret the novel words. Follow-up work has found similar abilities in 22-month-olds (Messenger et al., 2015) and 15-month-olds (Jin & Fisher, 2014).

Thus, there is ample evidence that children are sensitive to syntactic cues from an early age and use them as a source of information during word learning. Furthermore, computational models have been able to simulate syntactic bootstrapping from limited language input, acquire syntactic categories, and perform well in word-learning tasks (Alishahi & Stevenson, 2008; Brusini et al., 2021; Christodoulopoulos et al., 2016; Christophe et al., 2016). This supports the proposal that syntactic bootstrapping plays an important role in children's word learning. However, syntactic cues are useful especially because they are relatively stable across language—to what extent would children be able to bootstrap novel word meanings based on recently updated expectations, as in syntactic adaptation?

Havron et al. (2019) and the Current Studies

To sum up, both children and adults exhibit syntactic priming in comprehension and production. In addition, syntactic cues appear to play a key role in children's word learning via 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. Specifically, the study examined whether priming French-speaking 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. Children (and an adult comparison group) appeared 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, then upon encountering an unfamiliar word, English-speaking adults and children should look more at the image (action or object) matching the type of phrase (verb or noun) they heard during training trials.[1]

Experiment 1

Experiment 1 was a direct replication of Havron et al. (2019) that was carried out using web-based eye-tracking. This study 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.

[1] We preregistered all three experiments on the Open Science Framework 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.

Method

Participants

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

Procedure

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) and were downloaded from the authors' repository at https://osf.io/zzd9y/. Every participant was randomly assigned to either the noun condition (37 participants) or the verb condition (40 participants). Participants 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 showed 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.

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

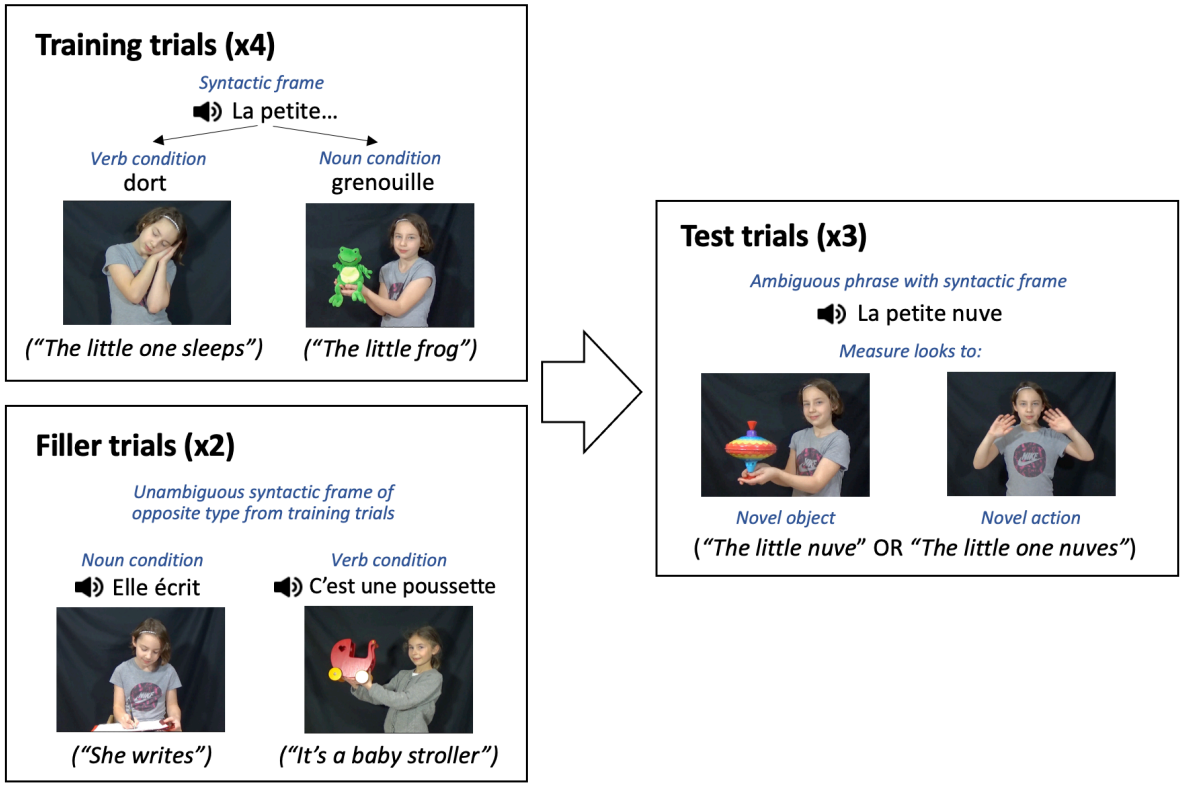

Figure 1. ***Diagram of experimental set-up for Experiment 1.***

preferred by the speaker during training trials, they should behave differently in the different 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; 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). WebGazer recorded 81% of total looks as being directed to the screen; the remaining 19% presumably reflected participants looking away or blinking, or WebGazer losing track of their gaze. 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 (46% of the total looks in the dataset). In the analyses, we report only the looks to the action video, because when only the regions of interest are examined, any look not to the action video is to the object video.

Results

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 videos 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).

We conducted a preregistered mixed effects linear regression analysis 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).

In the mixed effects linear regression, we predicted participants' 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 since there were only three test items. There was a 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 < 0.01).

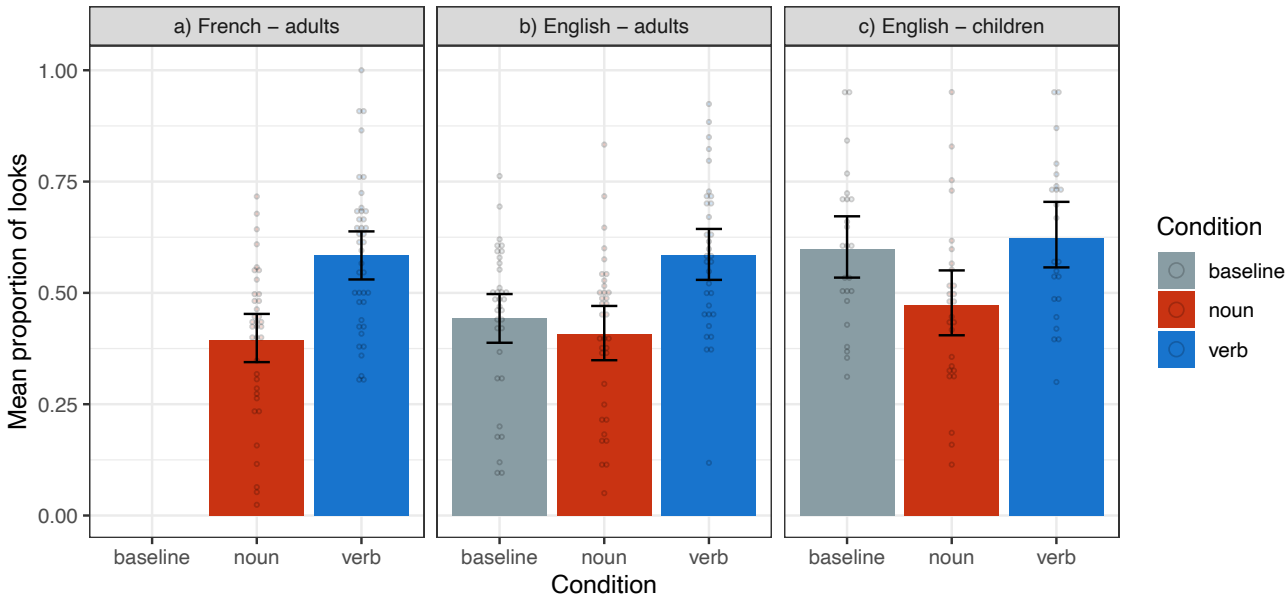

Figure 2. ***Mean overall proportion of looks to the action video or image for a) Experiment 1, b) Experiment 2, and c) Experiment 3. Results are shown for the noun, verb, and (when applicable) baseline conditions during test trials, with bootstrapped confidence intervals. Semi-transparent dots correspond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

[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 logistic regression analyses are reported in the Supplementary Materials.

Time Course

While the results for proportion of looks demonstrate that adults are indeed using syntactic adaptation 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 were 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, in Figure 3a we present a time course plot which suggests 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 showed participants the images before they heard the first instance of the novel words, in order to examine whether their looking patterns changed over the course of the trial.

Training and Filler Trials

We also conducted exploratory post-hoc analyses of training and filler trials 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 that 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 those in the noun condition (β = 0.518, SE = 0.044, $p < 0.001$). The pattern was reversed on 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.

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

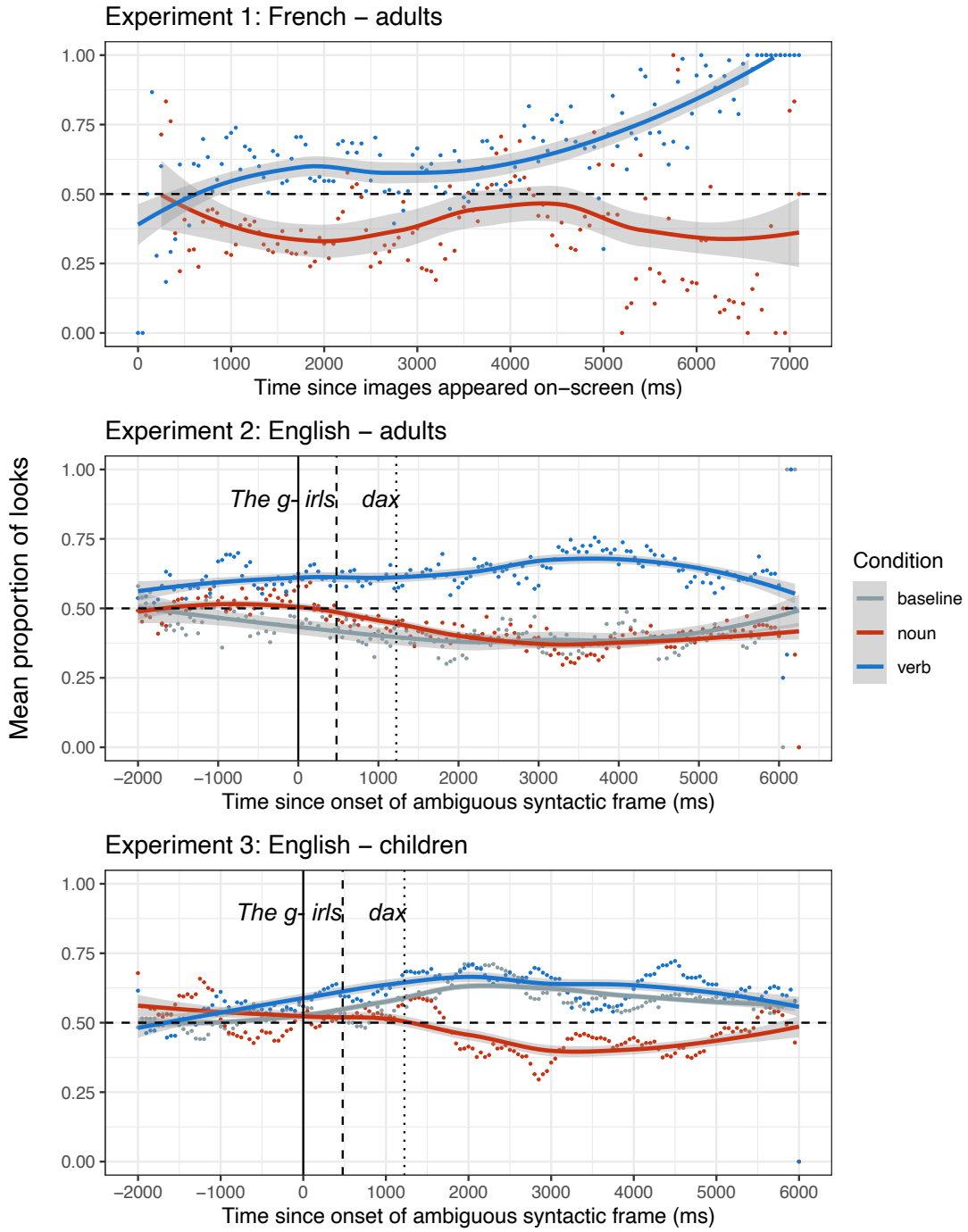

Figure 3. ***Proportion of looks to the action video or image over time on test trials of Exp. 1 (top), Exp. 2 (middle), and Exp. 3 (bottom). Gray areas represent overall confidence intervals. For Experiments 2 and 3, the zero point (indicated by the vertical black line) corresponds to the onset of the 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.***

Discussion

Experiment 1 directly 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 such that, 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 course data suggests that the effect remained consistent throughout the trial. Thus, we found evidence 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. The smaller effect size is not surprising given that it was a replication (Open Science Collaboration, 2015) and that online eye-tracking is noisier than eye-tracking with in-lab devices (Degen et al., 2021; Madsen et al., 2021; Semmelmann & Weigelt, 2018).

Is it possible that web-based eye-tracking is the wrong tool for investigating our questions of interests? We think not. First, despite the smaller effect size, we replicated the results of Havron et al. (2019). Furthermore, participants were quite clearly looking at the expected videos during both training and filler trials, when it was obvious which video was being described. WebGazer's rate of track loss in our study (19%) was just slightly worse than the upper range (11.1%—17.6%) reported in a study that compared 12 different in-lab eye-trackers with adults (Holmqvist, 2017), and it is on par with the values reported in a comparison of two in-lab eye-trackers (17% and 20%) with three-year-old children (De Kloe et al., 2022). This aligns with previous findings that WebGazer is slightly less accurate than in-lab eye-trackers (with an average offset of 207 pixels vs. 172 pixels for in-lab) and shows higher variance, while still replicating results established in lab-based eye-tracking (Semmelmann & Weigelt, 2018). In our experiment, the relatively low number of data points included in the analysis of looks to action vs. object video (46%) may be due to the conservative way we defined the regions of interest, such that they included just the coordinates of the videos themselves and a small amount of padding (150 pixels) on each side. Because of WebGazer's lower accuracy compared to in-lab eye-trackers, it may be preferable to define wider regions of interest—before beginning analysis—as in Yang & Krajbich (2021), who also replicated lab-based findings using WebGazer. This could help ensure that genuine looks to the region of interest are not excluded due to WebGazer's

lower accuracy.

WebGazer was not suited to fine-grained temporal analysis at the time our study was conducted, with previous visual world replication studies finding 300—700 ms delays in the time that effects appeared compared to the original studies (Degen et al., 2021; Semmelmann & Weigelt, 2018; Slim & Hartsuiker, 2022). However, its temporal resolution is substantially improved in newer versions (Vos et al., 2022; Yang & Krajbich, 2021). Overall, it is encouraging that the results of the original paper replicated using the novel method of web-based eye-tracking, and we expect that future versions of the WebGazer software will continue to increase its suitability for behavioral research.

One limitation of the study design in Experiment 1 is that there are four training trials but only two filler trials. While the filler trials indicate 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. Thus, the design results in participants being directed to look more frequently at action (verb condition) or object (noun condition) videos 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 can support word learning—in 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. If so, it would provide additional evidence for the role of syntactic adaptation as a general mechanism that can be drawn on during 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. First, 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 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

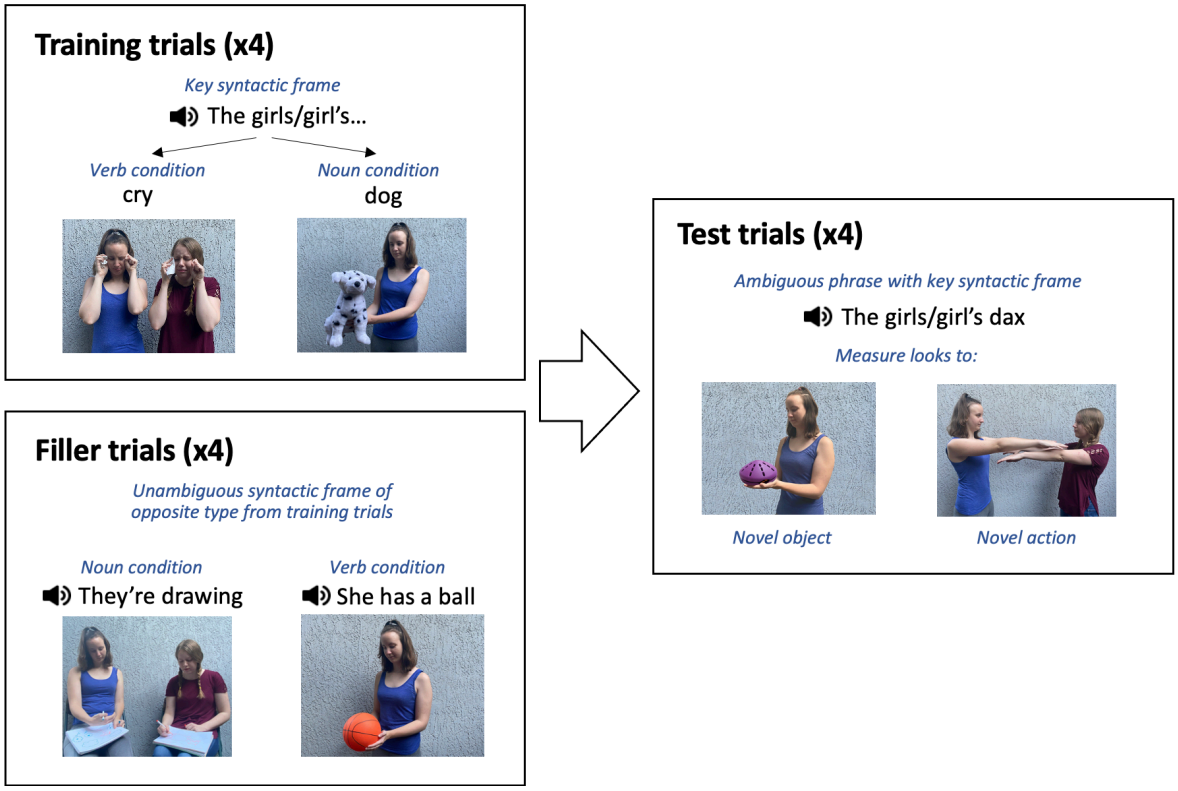

Figure 4. ***Diagram of experimental set-up for Experiments 2 and 3.***

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.

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/The 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. The inclusion of a baseline condition 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.

We ensured that participants were not biased toward a particular interpretation by factors such as prosody by running an online norming experiment beforehand with 30 adult participants who were native English speakers. In the norming study, we played only the audio clips (such as *The girls/girl's dax*) and asked participants whether they thought the novel word referred to 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.

On the final trial, we directly asked participants to click on the image they thought the narrator was talking about. The image selection 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 added the explicit measure only on the final trial to avoid potential interference with participants' eye movements.

Method

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).

Procedure

Besides the modifications described above, the experiment design was identical to Experiment 1. The number of trials was kept similar to Havron et al. (2019) due to limits in children's ability to maintain attention; the English version of the experiment lasted approximately fifteen minutes. Trial order was randomized, except that we did not allow more than two training or filler trials in a row. Image sides were counterbalanced.

Measures

Experiment 2 was carried out with WebGazer using the same measures as Experiment 1. WebGazer recorded 87% of looks as being directed toward the screen. Again, we analyzed only looks to the action image or the object image (62% of the total looks in the dataset).

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 noun condition (though not with the verb 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).[4]

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.

[4] Although the comparisons with the baseline condition are our primary statistical analyses, it may be of interest to directly examine the difference between the noun and verb conditions. In Experiment 2, participants in the verb condition looked at the action image significantly more than participants in the noun condition (β = 0.212, SE = 0.052, p < 0.01).

The time course plot reveals several interesting descriptive 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 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. The 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 conducted a post-hoc exploratory analysis examining whether there is a detectable change in looks before vs. after the linguistic event of interest: for each participants, on 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 proportion of looks for participants in the noun condition vs. the baseline condition ($\beta = -0.087$, $SE = 0.047$, $p = 0.068$), but no significant difference for participants in the verb condition vs. the baseline condition ($\beta = 0.06$, $SE = 0.048$, $p = 0.217$).

A likelihood ratio test between this model and a model without the effect of condition revealed an overall significant main effect of condition ($\chi 2(1) = 9.22$, $p < 0.01$), and the confidence intervals for the noun and verb conditions do not overlap. These results suggest 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 between conditions may have been driven by initial image preferences, the time course provides evidence that participants' looking patterns

[5] In fact, in another post-hoc 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 ($\beta = 0.147$, $SE = 0.048$, $p < 0.01$).

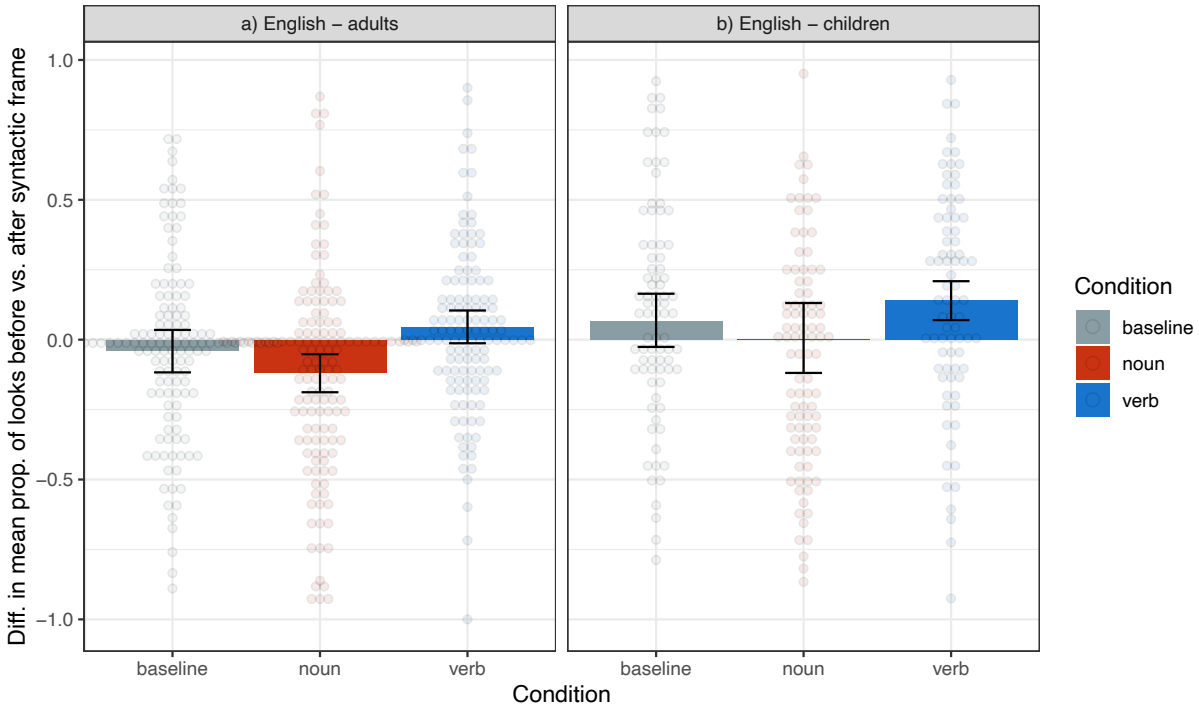

Figure 5. ***Mean overall difference in proportion of looks to the action image for a) Experiment 2 and b) Experiment 3. The difference is calculated by subtracting the proportion of looks before the end of "The g-" from the proportion of looks after the end of "The g-". Results are shown for the noun, 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).***

changed as the sentence unfolded. As shown in Figure 5a, the change was in the expected direction, with participants in the verb condition looking more at the action image and participants in the noun condition looking more at the object image.

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. To test these differences, we carried out post-hoc pairwise comparisons of the proportion of participants in each condition who selected the action image, using the Bonferroni adjustment for multiple comparisons. We found that

compared to participants in the noun condition, those in the baseline condition ($p < 0.01$) and the verb condition ($p < 0.01$) were significantly more likely to select the action image. There was not a significant difference between the baseline and verb conditions ($p = 0.81$). Despite having selection data for only one trial, the difference between the noun and verb conditions is quite striking: In their explicit judgments about the meaning of a novel word, participants tended to interpret the word in line with the examples they had heard during training trials, which were presented in the same syntactic frame.

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 the attenuation of effect size may be due to the noisiness of web-based eye-tracking. The rate of data loss was slightly lower than in Experiment 1, and we again defined regions of interest fairly conservatively; future experiments with WebGazer may wish to adjust this.

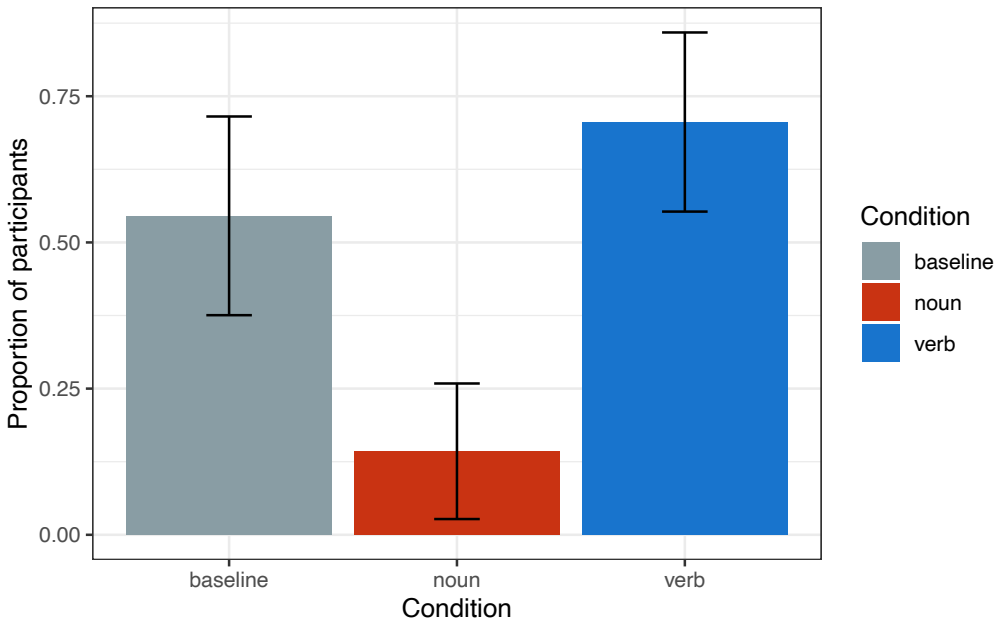

Figure 6. ***Proportion of participants in the baseline, noun, and verb conditions who selected the action image when explicitly asked to click on the image they thought the narrator was talking about.***

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. One possibility is that baseline participants were biased to think that *The girls/girl's X* was more likely to refer to an object image than an action image, either based on sentence prosody or on differences in the frequencies with which they hear the plural *The girls* and the possessive *The girl's…* preceding verbs vs. nouns.

To investigate the hypothesis that baseline participants were influenced by the distributions of the two structures, we conducted a corpus analysis using the Corpus of Contemporary American English (Davies, 2008), which draws from both speech and written text. In this analysis, we found 2,125 instances of *The girl's [noun]* and 1,013 instances of *The girls [verb]*. That is, the plural structure was half as frequent as the possessive structure. While these results align with baseline participants' preference for the object image, which matches the possessive *The girl's [noun]* interpretation of the structure, we have two reasons to doubt that baseline participants were drawing inferences about the meanings of the novel words.

First, the norming study we conducted before running the experiment did not find a preference for the noun or verb interpretation, suggesting that participants were not biased by prosody or by prior expectations about the meanings of the novel words. Second, the results we obtained using explicit selection on the final trial did not indicate that baseline participants were 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.

Thus, we favor a second possible explanation: participants in the baseline condition may have found the object images to be more salient or interesting. We consider this to be a plausible possibility because two other norming studies[6] found conflicting results regarding the salience of the object and action images. Participants in one norming study thought a speaker would be more likely to talk about the object images overall. However, in the second norming study, where images were matched 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

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

interesting than the action images.

On the whole, the results of Experiment 2 provide evidence 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.

Experiment 3

In Experiment 3, we extended the paradigm from Experiment 2 to ask whether three- to five-year-old English-speaking children would show similar patterns of syntactic adaptation during word learning. If children's behavior is similar to adults, it would support the proposal that adaptation is an important mechanism supporting child language acquisition.

Method

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 compared to adults; the sample size was similar to that of Havron et al. (2019). Children had to be native English speakers to be eligible for the study.

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.

Measures

Rather than using web-based eye-tracking, which proved to be noisy and frustrating for participants in pilot testing, 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.

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).[7]

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 the Experiment 2 adults, in Experiment 3, the children in all three

[7] Again, comparing the noun and verb conditions directly, children in the verb condition looked significantly more at the action image than did children in the noun condition ($\beta = 0.210$, $SE = 0.064$, $p < 0.01$).

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 preference 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 indicates that shortly after the beginning of the ambiguous syntactic frame, *The g-*, children's looking patterns began to diverge. Children in the noun condition appeared to look 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 in the trial.

As in Experiment 2, to determine the point in the trial at which these effects appeared, we performed a post-hoc exploratory analysis in which 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 used a mixed effects regression model to predict 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). 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]*. These updated expectations then guided their interpretation of an ambiguous novel word presented in the same syntactic frame, such as *The girls/girl's dax.* Participants in the verb condition exhibited a preference for looking at the action image over the object image on test trials, and vice versa for participants in the noun condition. This effect was weaker in children than adults, but present in both groups.

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 norming studies and the explicit selection task discussed in Experiment 2 provide evidence that adult participants in the baseline condition were not forming interpretations about the meanings of the ambiguous novel words.

Children, on the other hand, may have shown the opposite pattern from adults due to differences in their baseline expectations and preferences. Recall that in an adult corpus, we found about twice as many instances of *The girls [verb]* as *The girls [noun],* which aligned with baseline adults' preference for the object image. We carried out a second corpus analysis using the CHILDES corpus (MacWhinney, 2000) to examine child-directed speech, and found 10 instances of *The girl's [noun]* and 60 instances of *The girls [verb]*. That is, the plural structure was six times as frequent as the possessive structure. We are reluctant to draw conclusions from such a small sample, but it may be possible that the plural structure is relatively more frequent compared to the possessive structure in child-directed language than it is in adult language (including written text). Thus, children's baseline preference for the action image may be the result of a baseline expectation for the observed signal to underlyingly have the plural structure. If so, children in the noun condition could be displaying stronger adaptation to the more surprising structure, and vice versa for adults in the verb condition, which would align with the results of Havron et al. (2019) as well as Jaeger & Snider's (2013) finding that the more unexpected primes have bigger priming effects.

However, visual saliency effects could also have influenced both child and adult looking patterns in the baseline condition. For instance, children may have found the action images more salient because they featured two people in them, while adults may have found the novel objects in the object images to be more salient, because they are more knowledgeable about the improbability of encountering such objects in everyday life (children might be more likely to see similarly strange-looking toys). Further examination of children's baseline expectations for structures and their visual saliency preferences is needed to determine whether either of these factors, or both, drives the differences in the baseline condition for adults and children.

In addition to the overall looking time analyses, exploratory time course analyses provided some evidence that participants in the noun and verb conditions adjusted their looking patterns as they listened to the sentence unfold. Both children and adults showed differences in looking patterns, in the expected directions, before vs.

after the onset of the novel word. These effects appeared to be driven by participants in the noun condition for both adults and children (though the comparison with the baseline condition for adults did not reach significance). 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.

Our results are similar to the key findings of Havron et al. (2019). One contribution of our work was the equal number of filler trials and training trials in Experiments 2 and 3. This modification 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. The adaptation effect then guided participants' interpretations of an ambiguous novel word that was presented in the same syntactic frame.

Another 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. With continuing improvements to the software, WebGazer may become suitable for even finer-grained spatial and temporal analyses (Semmelmann & Weigelt, 2018; Yang & Krajbich, 2021).

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 in both language processing and language acquisition. In fact, Havron et al. (2021a) tested whether syntactic adaptation might allow children to update their interpretation of familiar homophones by exposing them to repeated uses of either *La petite [noun]* or *La petite [verb]*. When 3- to 4-year-olds then heard an ambiguous sentence such as *La petite ferme* (which could mean "The little farm" or "The little one is closing"), they tended to interpret the homophone as either a noun or a verb depending on which kind of sentences they had heard during training. The combination of these studies

illustrates that syntactic adaptation can affect both familiar word processing and novel word learning.

More broadly, the results of the current studies add to the growing literature emphasizing the role of prediction in language acquisition (Babineau et al., 2022). Prior work has called into question whether prediction operates during children's language learning or only in mature processing (Rabagliati et al., 2016). Recent work has found evidence that children can use semantic information to predict upcoming linguistic content from 2 years old (Gambi et al., 2018), and 4- to 5-year-olds were shown to be able to adapt their interpretations of a sentence to rely more on syntactic or semantic information depending on which cue had previously been reliable (Beretti et al., 2020). These studies suggest that children are not only able to make the kinds of predictions that could support language learning, but also adapt the type of information they are drawing on to make those predictions. Other findings have provided support for the claim that linguistic prediction skills may be linked to general vocabulary development in infants and children (Gambi et al., 2021; Mani & Huettig, 2012; Ylinen et al., 2016).

Havron et al. (2019; 2021) and the cross-linguistic extension of their findings reported here contribute to this literature by demonstrating directly that children can update their syntactic predictions and recruit them during novel word learning. As noted by Babineau et al. (2022), however, future work must examine the extent to which prediction plays a role in infants' language acquisition, as some studies have not found such abilities in children 2 or younger (Havron et al., 2021a; 2021b; Gambi et al., 2018)—although this finding could also be due to infants lacking sufficient linguistic experience on which to base their predictions. If prediction is demonstrated to figure significantly in language learning from an early age, it may allow us to provide a more unified account of language acquisition and processing.

Regarding syntactic adaptation specifically and its relationship to word learning, open questions remain about adults' and children's baseline expectations of 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. Furthermore, this research has concentrated on French and English thus far (children's linguistic prediction skills have been studied in German, in Mani & Huettig, 2012, but not how they may adapt those predictions). However, other languages may contain even more frequent examples of ambiguous structures where syntactic adaptation could be useful in children's learning of novel words.

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, we do not know whether the adaptation effect is speaker-specific or whether it could generalize to other speakers and contexts (adult studies have found conflicting results: e.g., Kamide, 2012; Kroczek & Gunter, 2017; Lu et al., 2021; Schuster & Degen, 2019; Yildirim et al., 2016). 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 phrase with differing lexical content. If children are likely to encounter repeated syntactic structures 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. A deeper understanding of the mechanisms of syntactic adaptation in children, including the extent to which it is specific and cumulative, would allow us to examine whether it is in fact a form of error-based learning that could contribute to syntax acquisition (Chang et al., 2006). Moreover, it will be important to study how syntactic adaptation may take place in naturalistic contexts, where children are likely to repeat or respond to novel words that they hear and begin to use them in conversation right away, rather than hearing them repeated multiple times uninterrupted by a single speaker (Clark, 2007). During language acquisition, syntactic adaptation could 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 that syntactic adaptation, and prediction more broadly, plays in children's language learning merits further investigation, these three experiments provide evidence that children and adults can not only flexibly update their expectations about a speaker's syntactic preferences, but also draw on these expectations to guide novel word learning.

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Data, code and materials availability statement

All stimuli, data, and analyses for all three experiments can be found at: https://github.com/eswanson166/syntactic-adaptation-and-word-learning.

Ethics statement

Data collection for these studies was approved by the Stanford Institutional Review Board (IRB), protocol 19960.

Authorship and contributorship statement

ES proposed the project, carried out data collection and analysis, and wrote the first draft of the manuscript. MCF and JD helped design the studies, provided advice on data collection and analysis, and reviewed and edited the manuscript. All authors approved the final version of the manuscript and agree to be accountable for all aspects of the work in ensuring that questions related to the accuracy or integrity of any part of the work are appropriately investigated and resolved.

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Supplementary materials

Mixed Effects Logistic Regression Analysis

The main analysis reported in the paper is the mixed effects linear regression predicting the arc-sin transformed proportion of looks to the action image during a trial. Across all three experiments, we also preregistered a mixed effects logistic regression analysis directly predicting individual looks to the action image. We chose

to carry out both analyses because each has advantages and drawbacks, with proportion of looks collapsing information about individual looks, while models of raw looks may not fully account for correlations between neighboring looks (though we did include previous look as a predictor). However, converging evidence from these two models would provide promising support for the hypothesis. Indeed, the results of the models agreed across all three experiments, so to save space, we only reported the linear regression on arc-sin transformed proportion of looks in the final paper. The results of the logistic regression on individual looks are summarized below.

Experiment 1

In Experiment 1, the mixed effects logistic regression predicted the log odds of looking to the action video as a function of condition and previous look (to the action video or not). It included a random intercept for participant and a random slope that accounted for participant differences in the effect of previous look. There was a significant main effect of condition ($\beta = 0.855$, SE = 0.175, $p < 0.001$), such that participants in the verb condition were more likely to look at the action video. There was also a significant main effect of previous look ($\beta = 4.761$, SE = 0.225, $p < 0.001$) such that if a participant looked at the action video on their previous look, they were more likely to look at the action video on the following look as well.

Experiment 2

Similarly, in Experiment 2, the mixed effects logistic regression analysis directly predicted the log odds of looking to the action image as a function of condition and previous look. It included random by-participant intercepts and a random by-participant slopes for previous look. Participants in the noun condition were marginally less likely to look at the action image compared to those in the baseline condition ($\beta = -0.395$, SE = 0.23, $p < 0.09$), while participants in the verb condition were marginally more likely to look at the action image ($\beta = 0.441$, SE = 0.231, $p < 0.06$). There was also a significant main effect of previous look ($\beta = 4.96$, SE = 0.245, $p < 0.001$) such that participants were more likely to look at the action image if their previous look was to the action image.

Experiment 3

In Experiment 3, the mixed effects logistic regression model again directly predicted the log odds of looking to the action image as a function of condition and previous look. As before, we included random by-participant intercepts and random by-participant slopes for previous look. This model also revealed a significant effect of condition, such that children in the noun condition were less likely than children in the

baseline condition to look at the action image (β = -0.263, SE = 0.101, p < 0.01). There was not a significant effect for children in the verb condition compared to children in the baseline condition (β = 0.138, SE = 0.106, p = 0.194). The effect of previous look was significant, such that if a child's look on the previous sample was towards the action image, their current look was also more likely to be directed towards the action image (β = 7.27, SE = 0.087, p < 0.001).

Exploratory Generalization Trial

In Experiment 1, following Havron et al., we included an exploratory generalization trial. On this trial, participants heard an ambiguous structure using the masculine *Le petit…* frame rather than the feminine *La petite…* that had appeared during training trials. Results indicated that participants in the verb condition looked significantly more to the action video than participants in the noun condition (β = 0.195, *SE* = 0.085, p = 0.024). Although we should be cautious given that it is based on a single trial, this finding suggests that syntactic adaptation may generalize to slightly different structures. Though this question was outside the scope of Experiments 2 and 3, it merits further investigation to determine the extent to which syntactic adaptation is structure-specific.

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