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Three- to Four-Year-Old Children Rapidly Adapt Their Predictions and Use Them to Learn Novel Word Meanings

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Adults create and update predictions about what speakers will say next. This study asks whether prediction can drive language acquisition, by testing whether 3- to 4-year-old children (n = 45) adapt to recent information when learning novel words. The study used a syntactic context which can precede both nouns and verbs to manipulate children's predictions about what syntactic category will follow. Children for whom the syntactic context predicted verbs were more likely to infer that a novel word appearing in this context referred to an action, than children for whom it predicted nouns. This suggests that children make rapid changes to their predictions, and use this information to learn novel information, supporting the role of prediction in language acquisition.

Prediction has been proposed to be a fundamental aspect of cognition, supporting multiple levels of cognitive processing and learning (Clark, 2013). In language processing, for example, there is evidence that adults form predictions as to the likelihood of different syntactic structures, and update these predictions whenever they encounter a structure that does not match their expectations. Adults' initial expectations are based on a lifetime of linguistic experience, but as researchers manipulate exposure to structures in the input, the expectation to encounter these structures increases or decreases rapidly (Fine, Jaeger, Farmer, & Qian, 2013; Kaschak, 2006; though see also Harrington Stack, James, & Watson, 2018). Adults might have developed the ability to flexibly change their predictions through their lifelong expertise with language, as suggested by studies showing an increase in prediction in older ages (e.g., Huettig & Janse, 2012) and with literacy (Mishra, Singh, Pandey, & Huettig, 2012). However, it may also be that adults' ability to adapt to the current linguistic environment is a consequence of language learning occurring through prediction and error minimization. In this vein, several researchers have proposed that prediction is important for language acquisition (e.g., Chang, Dell, & Bock, 2006; Gambi, Pickering, & Rabagliati, 2016; Ylinen, Bosseler, Junttila, & Huotilainen, 2017). To explore this question, we examine whether 3- to 4-year-old children draw on recently encountered information to revise their predictions about the likely syntactic category of upcoming words, and exploit these revised predictions to infer novel words' meanings.

We draw on two lines of research: Findings from the priming literature suggesting that children revise their syntactic expectations both in production and comprehension (e.g., Peter, Chang, Pine, Blything, & Rowland, 2015; Thothathiri & Snedeker, 2008); and evidence that infants can use syntactic context to infer the meaning of novel words (e.g., Bernal, Lidz, Millotte, & Christophe, 2007; Huang & Arnold, 2016; Oshima-Takane, Ariyama, Kobayashi, Katerelos, & Poulin-Dubois, 2011; Waxman, Lidz, Braun, & Lavin, 2009).

Research on *syntactic priming* in children—that is, their tendency to reuse recently encountered

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structures and process them faster—provides evidence that children learn from the distribution of structures in their input. Branigan and Messenger (2016) found that children's production of passives increased after priming, and increased even more in a second session held a week later. This suggests that priming is not just a result of activation of syntactic representations, but a manifestation of learning through adjusting expectations to the distribution of structures in the input. Recent studies also found that the more surprising or infrequent a prime is, the larger the priming effect children show—as predicted by error-based learning models of priming (e.g., Peter et al., 2015). Nonetheless, these findings do not speak to the crucial question of whether children's revised expectations are used when encountering unfamiliar input, such as novel words. To test whether children use their adapted expectations to learn, we focus on children's prediction of a novel word's syntactic category from its linguistic context.

Children create expectations about the syntactic category of a following word, by relying on the distribution of structures in the input. For example, articles are usually followed by nouns (which tend to denote objects or agents), and pronouns are usually followed by verbs (which tend to denote actions). Infants as young as 18 months can already use these contexts to infer the possible meaning of novel words. When listening to a sentence like "It's a dax," they infer that "dax" refers to an object. Likewise, when listening to a sentence like "It's daxing," infants infer that "dax" refers to an action (He & Lidz, 2017). This *syntactic bootstrapping* may account for children's ability to rapidly learn the meaning of novel words (Gleitman, 1990).

Although children are able to exploit context to build expectations about what will come next, there is little direct evidence that children update expectations rapidly enough to affect learning, and most importantly, no evidence that these updated expectations can guide the learning of novel linguistic information (Rabagliati, Gambi, & Pickering, 2016). In this study, we ask whether exposure to a small amount of input that children can successfully process, triggers changes to their predictions about syntactic categories, when confronted with novel words. We manipulate the distribution of familiar nouns and verbs, within a syntactic frame which can contain either a noun or a verb. We present one group of children with this frame preceding familiar nouns, and the other with this same frame preceding familiar verbs. We expect that children will use this distributional information to infer the syntactic category of a novel word appearing in this context—expecting this novel word to be a noun if they have heard familiar nouns in this context, and to be a verb it they have heard familiar verbs in this context. If they do, this would be the first evidence that children's expectations are updated rapidly enough to allow prediction-based learning, and most importantly, that these adjusted expectations can guide language acquisition. This would simultaneously support a unified account of language processing and language learning, and shed light on the mystery of the speed and accuracy of children's language acquisition.

Method

All data and materials have been made publicly available via the Open Science Framework (OSF) and can be accessed at https://osf.io/zzd9y/. The design and analysis plans were preregistered at the OSF and can also be accessed with the same link.

Participants

Our final sample consisted of 45 monolingual French-speaking children between the ages of 39.1 and 50.6 months (23 in the verb condition, 13 boys and 10 girls, M_{age} = 45.3 months, SD = 3.26; 22 in the noun condition, 9 boys and 13 girls, M_{age} = 45.4 months, SD = 3.3). They were recruited and tested in a middle- to high-socioeconomic status school in Paris, or in our babylab through direct contact with parents belonging to our database (these children can also be assumed to come from middle- to high-socioeconomic status homes). The children were tested between March and April 2017. Of 55 children originally tested, 4 were removed for technical difficulties, 3 for fussiness and crying, and 1 for naming the unfamiliar objects (e.g., saying "anteater" for a stuffed-animal we used in one video). We removed trials with more than 50% missing data, as well as any child with more than two missing trials, resulting in the exclusion of two more children. Written parental consent was obtained for all children.

We also tested 47 adult university students, 23 in the verb condition and 24 in the noun condition, as a control group. We report their results briefly, with the full data and results available on the OSF.

Design

In French, *la petite* can either be followed by a noun (e.g., *la petite grenouille*, "the little frog") or by

a verb (e.g., *la petite dort*, "the little one is sleeping"). It is more likely to be followed by a noun: a search in the Paris child-directed-speech corpus (Morgenstern & Sekali, 2009) found 720 instances where it was followed by a noun, and only six where it was followed by a verb. We manipulated the syntactic category that this context predicted by randomly assigning children to one of two conditions—a verb condition and a noun condition. In the induction phase, the verb-condition children were exposed to sentences in which *la petite* was predictive of verbs, that is, it was consistently followed by familiar verbs; whereas the noun-condition children were exposed to sentences in which it was predictive of nouns—consistently followed by familiar nouns. This phase was meant to create expectations for a different syntactic category in the different groups. In the test phase, we examined whether children utilize their adapted expectations to infer the meaning of novel words. If children adapted their expectations based on the few sentences they heard, then when hearing the same frame followed by a novel word (which could refer to either an action or an object), children from the verb condition should be more likely to look at a girl performing a novel action, compared to children from the noun condition; such a result would suggest they were more likely to categorize the novel word as a verb, on the basis of its preceding syntactic context.

Materials and Procedure

Participants were tested individually either in a quiet room in their school, or in our babylab in a sound-attenuated double-walled booth. They were sitting facing a 27-in. screen positioned 70 cm away from them. Eye gaze was recorded by Eyelink-1000 placed below the screen (operating in remote mode). We used a 5-point calibration.

The induction phase included six trials—four induction trials and two fillers. On each of these trials, the participant saw two videos played side-by-side-on the screen: one showing a little girl performing an action, and another showing the same girl holding an object. We showed the same girl on both sides of the screen to prevent participants from choosing which one is *la petite* based on which child they judge to be smaller or younger. During the presentation of the two videos side-by-side, a women's voice (the last author) asked the child to look at one of the videos in a child-friendly fashion. For instance, for the pair of videos showing a girl holding a frog on one side, and a girl sleeping on the other side, participants assigned to the noun condition would hear a sentence such as *Oh, regarde, la petite grenouille!*—"Oh look, the little frog!." In contrast, participants assigned to the verb condition would hear *Oh, regarde, la petite dort!*—"Oh look, the little one is sleeping!." For a sample trial see Figure 1. The prosody was the same for noun and verb sentences. This was done by intentionally picking a prosody that is appropriate for both nouns or verbs, in which the three words belong to the same prosodic phrase; otherwise it would have been possible to disambiguate using different prosodic structures (as shown in de Carvalho, Dautriche, & Christophe, 2016; de Carvalho, Dautriche, Lin, & Christophe, 2017; see Figure 2 for a graphical depiction of the prosodic contour, see a full acoustic analysis on the OSF).

Two of the trials from the induction phase were filler items, which used an unambiguous syntactic structure (either *c'est une Noun*, "it's a Noun" or *Elle Verb*, "she's Verbing"), and directed the children to look at the opposite video. For example, if a participant was in the verb condition, they heard four *la petite Verb* sentences (e.g., *la petite dort*, "the little one is sleeping") and two *C'est une Noun* sentences (e.g., *c'est une poussette*, "this is a baby-stroller"). We used these two fillers so that participants are not always asked to look at the action (or the object in the noun condition), but instead, realize that the woman can refer to either of the two videos. A difference between the two groups in the test phase should not therefore be attributed to them predicting that the woman in the experiment will always talk about the actions (or the objects), but to them predicting that the specific phrase *la petite* will be followed by either a verb or a noun. The order of the trials was randomized.

In the test phase, consisting of three trials, participants still saw two videos, but this time the little girl in the videos was performing a novel action (which does not have a name in French) or holding an unfamiliar object (which does not have a name in French). While watching the videos play side by side, the participant heard *Oh, regarde, la petite Novel-Word*, "oh look, the little one is Novel-Wording"/"the little Novel-Word" (e.g., *Oh, regarde, la petite nuve!* "Oh look, the little one is nuving"/"the little nuve!"). The three test trials featured three different novel words (*nuve*, *dase*, and *bamoule*), each presented with one novel object and one novel action. Children in both conditions saw the same videos and heard the exact same sentences. The prosody of the test sentences was the same as that

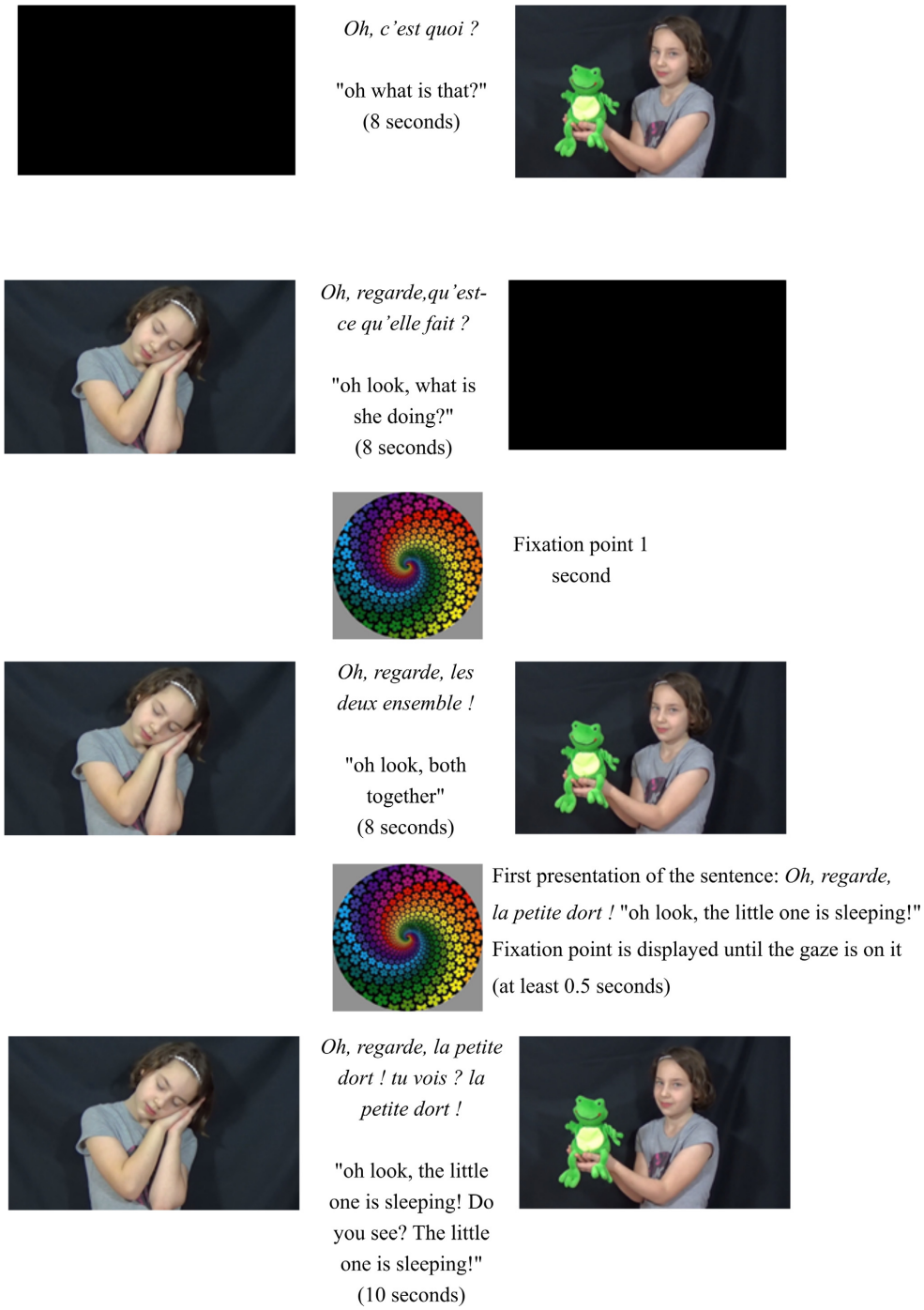

Figure 1. Sample trial (target side is counterbalanced).

of the induction sentences—ambiguous as to whether the final word is a noun or a verb. Note that even if there remain some prosodic cues that bias toward one interpretation (verb or noun), this does not affect the validity of the experiment, since both groups hear the exact same sentence, while watching the same videos. Therefore, the prosody cannot create any artefactual difference between groups. In order to ascertain that it is possible to interpret the novel word in the test sentences as referring either to a noun or a verb, we conducted an online survey, in which 26 adult native French speakers were asked to listen to the test sentences (without the visual context), and choose whether

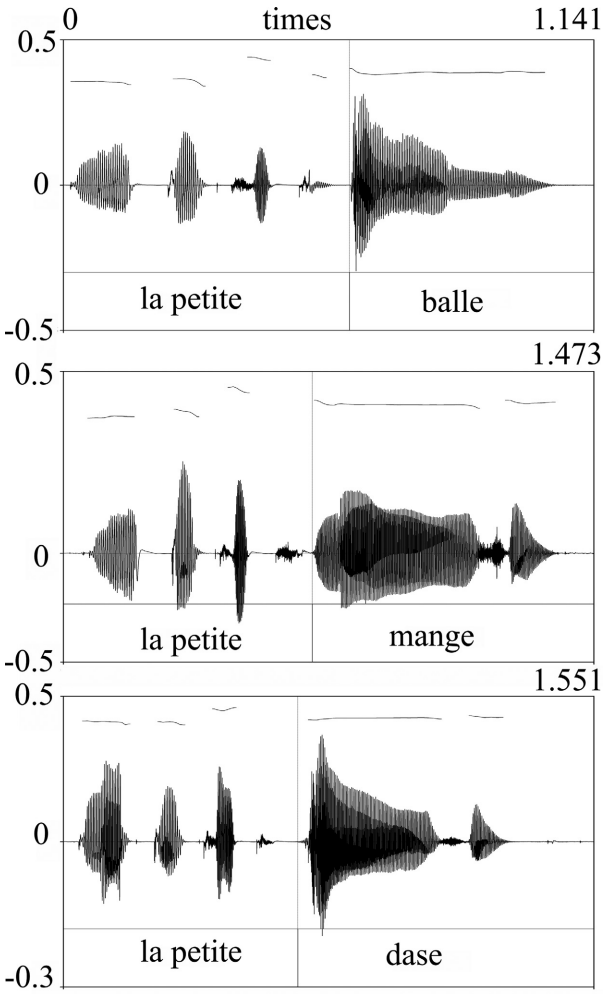

Figure 2. Soundwave and pitch for one noun phrase (*la petite balle*, top), one verb phrase (*la petite mange*, middle), and one phrase with a novel word (*la petite dase*, bottom).

the novel word referred to an object, or to an action that a girl is performing. Participants judged the novel word to have referred to an action 31% of the time, confirming that the novel word could be interpreted as either a noun or a verb.

Each trial lasted less than a minute, with the full experiment lasting about 8 min.

All videos can be accessed on the OSF.

Additional Information

In a fourth and final test trial, participants watched a boy perform a novel action and the same boy holding a novel object, they were directed to look at *le petit pirdale*. Since participants were always exposed to *la petite*, and never to *le petit* (masculine version of *la petite*), we wanted to see whether what they have learned would generalize to *le petit*. This single trial is purely exploratory and we report the full results on the OSF.

Statistical Analysis

To test our hypothesis that children will use the information they were exposed to in the induction phase to infer the meaning of the novel words in the test phase, we conducted two statistical tests.

We first ran a cluster-based permutation analysis testing for a significant difference between conditions (as, e.g., in Dautriche, Swingley, & Christophe, 2015; see Maris & Oostenveld, 2007, for a formal presentation of the analysis itself). We used R (R core team, 2017) and the package eyetrackingR (Dink & Ferguson, 2016), and first down-sampled the data by averaging to one sample every 20 ms. For each time sample, the analysis runs a mixed-effects model testing for the effect of condition (on the arc-sin transformed proportion of looks toward the action video) with a random intercept for participant (we did not add a random intercept for item because there were only three items). Adjacent time-points with a t-value greater than a predefined threshold (t = 1.5) are grouped together into a cluster. This analysis was conducted on the entire trial (0–10 s from the beginning of the trial). Note that an effect may exist from the beginning of the trial since participants have heard the sentence played one time before the videos reappeared. Our preregistered analysis was a cluster-based permutation analysis with a t-test, since at the time of preregistration, we had no way to run a mixed-effects permutation analysis. Results for the t-test permutation analysis are similar, and available on the OSF.

Our second analysis was a mixed-effects regression (using the *lme4 package*, Bates, Maechler, Bolker, & Walker, 2015) comparing the overall looking time at the action video, averaged across the whole trial, between the two conditions. The analysis included a random intercept for participant. We added the analysis of the overall looking time for two reasons: First, the cluster-based permutation analysis is a conservative test. Since we make no prior assumptions about when our effect will happen, we lose power when the effect is not highly situated, which can be expected in such an ambiguous context. Second, even strong advocates for this analysis recommend to supplement it by a more standard comparison of looking time (Delle Luche, Durrant, Poltrock, & Floccia, 2015).

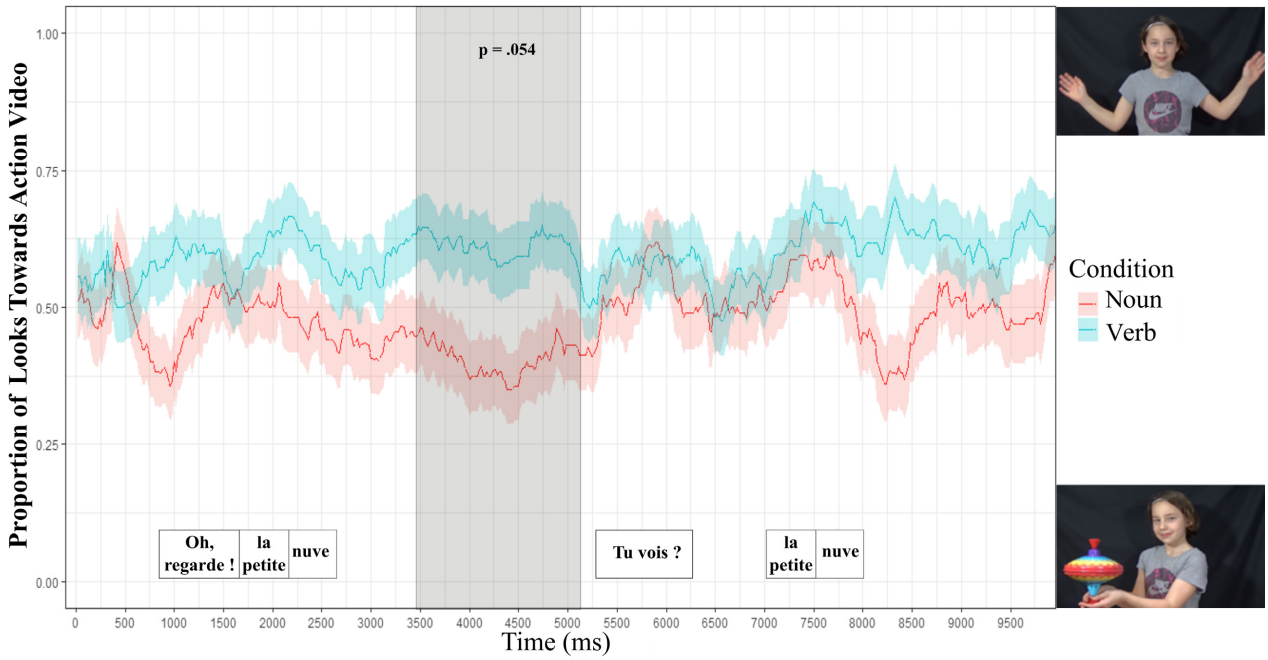

Figure 3. Proportion of looks toward the action video in the test phase for the two conditions. Proportion of looks toward the action video, as a function of time, plotted for the entire duration of the trial (verb condition in blue, noun condition in red). The shaded area denotes the cluster which was marginally significant. Children from the verb condition are consistently looking more at the action video than children from the noun condition (note that the target sentence was also heard once just before the beginning of the trial).

Results

The cluster-based analysis revealed a marginally significant cluster (p = .054), between 3,360 ms and 5,100 ms after the beginning of the trial, coinciding with the first repetition of the target word during the test (see Figure 3): during that time-window, children from the verb condition looked more at the action video than children from the noun condition.

The mixed-effects regression conducted on the average overall looking time per participants found a large effect of condition: Children from the verb condition (M = .602, SD = 0.117), were significantly more likely to look at the action video than children from the noun condition (M = .482, SD = 0.139, β = .189, SE = .06, t = 3.142, p = .003, Cohen's d = .941), suggesting that children from the verb condition were more likely to interpret the novel word as referring to the action than children in the noun condition (see Figure 4).

Adult Control Group

We found the same effect of condition in adults as we did in young children, except that the difference between conditions was larger for adults. The full results can be accessed on the OSF.

Discussion

In this study, we investigated whether children create predictions about the distribution of syntactic categories in a new environment, and draw on these to acquire word meanings. We found that children who heard examples of *la petite + familiar verbs* were more likely to infer that a novel word produced after *la petite* referred to an action, than children who heard *la petite + familiar nouns* sentences. This suggests that children did not only rapidly adapt their expectation to encounter a specific syntactic category (as was previously found in priming studies with children of this age, e.g., Thothathiri & Snedeker, 2008), but also utilized their adapted predictions to learn. Importantly, our design included filler items within the induction phase, to exclude the possibility that children were biased to look at the action video (or object video) without having to take into account the specific sentences—it is thus unlikely that our effect is the result of a simple bias for either action or object videos. This is the first study demonstrating that children adapt their predictions and use these adapted predictions to guide their learning of novel linguistic input.

One limitation of this study is that since we do not have a control condition with no induction, it is

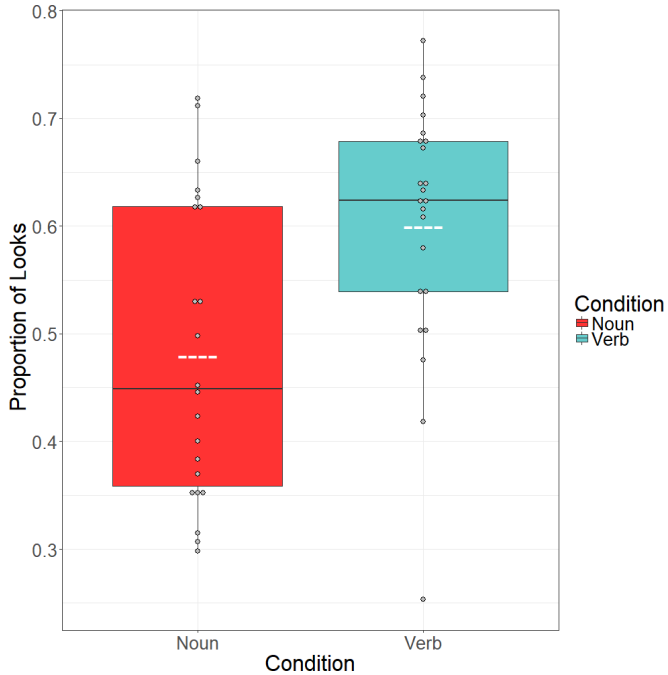

Figure 4. Mean overall proportion of looks toward the action video in the test phase for the two condition. Proportion of looks to the action video, averaged over the entire duration of the trial (verb condition in blue and noun condition in red). Gray dots represent individual participants. The lower and upper hinges correspond to the first and third quartiles, the dotted white lines represent the means, and the black lines within the squares represent the median. The top whiskers denote the maximum value, and the bottom whiskers the minimum value (note that one participant in the verb group is an outlier—he was *not* removed from any of the analyses). Children from the verb condition are looking at the action video significantly more than children from the noun condition.

possible that only children in one condition changed their predictions; for instance, children in the noun condition might have looked at the novel object because it was the default choice of interpretation, meaning only the verb-condition children changed their predictions. This would be in-line with previous studies, which found larger priming effects for the less-frequent structure (e.g., Kholodova, Peter, Rowland, & Allen, 2017).

Children showed different expectations after only four induction trials, which implies rapid adaptation and high sensitivity to structures in the input. This rapidity would be particularly useful since words seem to follow a "bursty" distribution in language (Altmann, Pierrehumbert, & Motter, 2009). Parents may repeatedly use *la petite* + *verb* when talking about a doll or a little girl, but revert back to the more common *la petite* + *noun* when changing the subject. It would be interesting to test in the future whether children form predictions that are conditioned on the context or speaker, as has been found in adults (e.g., Kamide, 2012; Kroczek & Gunter, 2017)—or whether they would also generalize to new speakers and contexts.

This experiment could be interpreted as showing that information provided to the language-processing system affects the language-learning system. However, in the sense that processing changes children's expectations, it produces the same kind of effect that we would normally call *learning*, and there is no sense in talking about two different systems. Language acquisition is in fact a process by which the child is learning to process language (Chang et al., 2006; Pickering & Garrod, 2013). As the child hears *la petite* before familiar verbs, she processes these sentences to both comprehend them, and change the model she relies on for processing and learning novel linguistic materials. Thus, whether the next sentence contains a word she knows (processing) or she does not know (learning), she will rely on her adapted expectations, to predict to what category the word following *la petite* will belong.

Our findings show that prediction does not only facilitate, but also guides learning. This means that predictions do not only help children learn by reducing the cost associated with processing the input, thus clearing resources for learning—they also

structure the space of possibilities for meaning. As to the exact mechanisms by which children compute and use their expectations, there are several possible accounts. Under the predictive-coding framework, the brain is thought of as a prediction machine, whose role is to capture the structure of input it encounters. The brain accomplishes this by predicting future input, and correcting its predictions when it encounters a prediction error. This is achieved through a hierarchical generative model that aims to minimize error within a bidirectional cascade of information (Clark, 2013; Sohoglu, Peelle, Carlyon, & Davis, 2012). Our results are in line with such a mechanism, but they are also in line with other mechanisms of learning through prediction. For example, children could be creating predictions using analogy (see Bar, 2007); or they could be updating their predictions by cumulating frequencies—not privileging evidence of error over correct predictions (for a discussion of the difference between this account and error-based predictions, see Corlett et al., 2004).

The importance of our findings does not apply only to ambiguous sentences containing novel words. They might also explain how children initially learn unambiguous contexts. According to the *semantic seed* hypothesis (Christophe, Dautriche, de Carvalho, & Brusini, 2016), infants could manage to learn the meaning of a handful of very frequent words (Bergelson & Swingley, 2012, 2013), group them into objects and actions (Carey, 2009), and use these known words to learn to predict action words after certain linguistic contexts, and object words after others. They may then use these expectations to constrain the meaning of novel words (Gleitman, 1990; He & Lidz, 2017). Our results illustrate how children rapidly form these predictions, and suggest a mechanism which could be useful not only in cases where the structure is ambiguous, but also for fully unambiguous syntactic contexts (such as articles and personal pronouns).

To conclude, it was previously suggested that children make rapid changes to their linguistic expectations following exposure to new linguistic evidence, and that they use this information when processing and learning new linguistic materials. We found that three- to four-year-old children indeed make rapid use of prediction at the syntactic level, and use newly adjusted expectations to infer novel word meaning. Prediction may thus be a key component not only in language processing in expert language users, but in children's language acquisition.

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