Prediction error boosts retention of novel words in adults but not in children.

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Abstract

How do we update our linguistic knowledge? In seven experiments, we asked whether error-driven learning can explain under what circumstances adults and children are more likely to store and retain a new word meaning. Participants were exposed to novel object labels in the context of more or less constraining sentences or visual contexts. Both two-to-four-year-olds (M_{age} = 38 months) and adults were strongly affected by expectations based on sentence constraint when choosing the referent of a new label. In addition, adults formed stronger memory traces for novel words that violated a stronger prior expectation. However, preschoolers' memory was unaffected by the strength of their prior expectations. We conclude that the encoding of new word-object associations in memory is affected by prediction error in adults, but not in preschoolers.

Keywords: prediction error; mutual exclusivity; disconfirmed predictions; memory retention; word learning.

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Children learn new words at a staggering rate (Fenson et al., 1994), demonstrating a remarkable ability not only to determine what a new word means, but also to retain huge numbers of form-meaning pairs in memory (Vlach, 2019). This learning extends into adulthood and indeed is lifelong, as new terms and vocabulary enter our language, and as we move between different linguistic communities (Ameel, Malt, & Storms, 2008; Borovsky, Kutas, & Elman, 2010; Hulme, Barsky, & Rodd, 2019). In this work, we investigate what factors affect our ability to retain word meanings, and whether these are the same in children and adults. In particular, we test how the retention of novel form-meaning pairs is affected by prediction errors, following theoretical claims that the computation of prediction errors drives memory encoding (Henson & Gagnepain, 2010).

There is now ample evidence that our interactions with the world are guided by prediction, from the way we control our movements (Wolpert & Flanagan, 2001) to how we make sense of our perceptions (Clark, 2013; Friston, 2005; Grush, 2004). Across these different domains, we are able to generate expectations about the future state of the world and, critically, we compare these expectations to information about the actual state of the world when it reaches our senses. This process of comparison between expected and observed states generates prediction error signals, which are thought not only to drive immediate behavioral responses, but also to affect long-term encoding of information in memory (Henson & Gagnepain, 2010), and thus our learning (e.g., Den Ouden, Friston, Daw, McIntosh, & Stephan, 2008; Niv & Schoenbaum, 2008; Rescorla & Wagner, 1972).

Importantly, prediction error is the result of a comparison between expected and observed states, and thus its magnitude depends on the strength, or precision, of both the information we receive from the outside world and of our prior expectations (Friston, 2005, 2010). Under the Predictive Interactive Multiple Memory Systems (PIMMS) framework proposed by Henson and Gagnepain (2010), larger prediction errors (i.e., greater mismatches between expected and observed states) lead to the formation of stronger memory traces. Combined with the idea that stronger (i.e., more precise) expectations generate larger prediction errors (when disconfirmed), this leads to a key hypothesis: Stronger expectations that are disconfirmed should benefit memory more than weaker expectations that are disconfirmed. While this may seem surprising and even counterintuitive (after all, incorrect expectations are akin to mistakes and making mistakes should impair memory for the correct answer), it falls out of the way prediction error is defined in these accounts – that is, as the discrepancy between expectations and input.

For example, Greve and colleagues showed that adults were more likely to remember the association between a scene and a new face (observed only once) if the scene had previously been repeatedly paired with another face (i.e., the same face multiple times), compared to several faces all different from the new face (Greve, Cooper, Kaula, Anderson, & Henson, 2017). Crucially, although in both instances the new face violated a previously established association (i.e., it disconfirmed an expectation), the previously-established association supported a stronger expectation when the scene was paired repeatedly with the same face. Thus, this finding confirms a key hypothesis derived from accounts of memory based on the computation of prediction error.

But does prediction error also affect our memory for word meanings? Surprisingly, despite a lot of recent interest in adults' and children's ability to predict upcoming language (Huettig, 2015; Kuperberg & Jaeger, 2016; Pickering & Gambi, 2018; Pickering & Garrod, 2013; Rabagliati, Gambi, & Pickering, 2016), the answer to this question is still unclear. While much evidence demonstrates that adults and young children are capable of generating expectations at multiple linguistic levels (Pickering & Gambi, 2018; Rabagliati et al., 2016), including meaning (Altmann & Kamide, 1999; Borovsky, Elman, & Fernald, 2012; Lindsay, Gambi, & Rabagliati, 2019; Mani, Daum, & Huettig, 2016; Mani & Huettig, 2012), structure (Gambi, Pickering, & Rabagliati, 2016; Havron, de Carvalho, Fiévet, & Christophe, 2019; Lukyanenko & Fisher, 2016; Wicha, Moreno, & Kutas, 2004), and perhaps form (Dikker, Rabagliati, Farmer, & Pylkkänen, 2010; Ylinen et al., 2014; but see Gambi, Gorrie, Pickering, & Rabagliati, 2018), comparatively little work has examined the consequences of disconfirmed expectations on memory for novel word meanings.

Prediction Error and Language Learning

The idea that prediction errors influence language learning is not new, and indeed a number of historically important models have made the claim that prediction errors play a critical role in children's language development. In these models, prediction error typically acts as a guide for learning; it offers a signal for when the learner should (or should not) revise their linguistic knowledge. For instance, Elman (1990; see also St. John & McClelland, 1990) introduced the idea that prediction error-driven learning could help a simple recurrent connectionist network acquire approximate linguistic representations: The network was trained to predict the next word in a large corpus of text and, when an encountered word mismatched its prediction, the model's internal representations were revised through backpropagation of error (Rumelhart, Hinton, & Williams, 1986). These ideas have also been highly influential for newer models of grammatical development (e.g., Chang, Dell, & Bock, 2006; Dell & Chang, 2014) and word learning (Plaut and Kello (1999). In addition, related ideas about error-driven learning can be seen in models that use theories of reinforcement learning to explain language development. For instance, Ramscar, Yarlett, Dye, Denny, and Thorpe (2010) argued that a model based on the Rescorla-Wagner learning rule (Rescorla & Wagner, 1972) can capture how children acquire word meanings under conditions of referential uncertainty, because the computation of prediction errors allows the child to discriminate between the situations in which a word can or cannot be used (see also Ramscar, Dye, & McCauley, 2013b). Thus, across all of these models, prediction errors guide children in forming linguistic representations that can accurately predict the linguistic input that they are likely to encounter.

In the PIMMS framework (described above), prediction errors also guide learning, but they do so by indexing how robustly the learner should encode a piece of encountered information into memory. Specifically, unexpected information (i.e., information that generates a larger prediction error) is encoded more strongly and thus can be retrieved more easily in the future. For the task of learning a word, this framework highlights that prediction errors could influence how learners remember and retain word meanings over longer periods of time. While this is not fundamentally different from the models reviewed above, in those models the focus is on how learners discover the meanings of words through experience (for examples see Ramscar et al., 2010; Grimmick, Gureckis, & Kachergis, 2019; Stevens, Gleitman, Trueswell, & Yang, 2017): Prediction errors generated by current input guide changes in linguistic representations and ensure that the system can accurately predict future input. The PIMMS framework instead focuses on prediction error's influence on retention of novel information in memory, which is the topic we address here, in both adults and children.

At least since Carey and Bartlett (1978), it has been recognised that young children can accurately retain word meanings in long-term memory, though exactly how much they are able to retain and under what conditions has been debated (e.g., Horst & Samuelson, 2008; Spiegel & Halberda, 2011; Vlach & Sandhofer, 2012; see Samuelson & McMurray, 2017, for review). In any case, to the extent that children do retain word meanings, this long-term retention appears to rely on domain-general memory mechanisms (Markson & Bloom, 1997, Vlach, 2019; Vlach & DeBrock, 2017). For instance, children's ability to retain word meanings up to one month is roughly matched to their ability to retain non-linguistic factual information over the same length of time (Markson & Bloom, 1997; Vlach & Sandhofer, 2012), and their memory for word meanings is affected by factors that are known to influence memory for non-linguistic information, such as repetition and spacing (e.g., Sandhofer & Vlach, 2011) and sleep (e.g., Henderson, Weighall, Brown, & Gaskell, 2012). While adults' retention rates for novel word meanings can be higher than children's, they are similarly matched to their retention rates for novel non-linguistic information (Markson & Bloom, 1997; Sandhofer & Vlach, 2012).

Given these considerations, and the findings that prediction errors influence memory for non-linguistic information in adults, we might expect prediction error should also affect the retention of word meanings over time, such that retention accuracy is greater for words that are learned in unexpected contexts. However, the prior evidence for this is actually somewhat unclear, as we review below.

Adults. We are not aware of any study that has tested how prediction error affects retention of newly-learnt word meanings in adults. However, a small number of studies do provide indirect evidence for a role of prediction error in adult word learning. Fitneva and Christiansen showed that adults perform better in a learning task when they encounter a greater proportion of word-referent mappings that are unexpected (Fitneva & Christiansen, 2011, 2017). Using a cross-situational learning paradigm, where novel words are repeatedly presented under situations of referential ambiguity (i.e., with multiple potential referents for each word; Yu & Smith, 2007), they exposed learners to word-referent mappings that were unexpected because they differed from those trained during an initial familiarization phase. Other mappings were instead expected, as they did not differ from those established during the familiarization phase. Strikingly, when the proportion of unexpected to expected mappings was higher, adult learners actually learned more compared to when the proportion of unexpected mappings was lower.

But while this finding may suggest that prediction error plays a role in adult word learning, it is unclear whether this interpretation is correct. According to a prediction error account, participants generated expectations about the words they were going to hear based on the mappings established during the familiarization phase and, the more often these expectations were then disconfirmed (because many mappings had changed), the more the resulting error signals benefitted learning of new word-referent pairings. But if this advantage stems from prediction errors, then it should be specific to the unexpected mappings – because it is only for these items that the learner should generate incorrect expectations. In contrast, Fitneva and Christiansen (2011, 2017) found that both unexpected and expected mappings were learned better when the proportion of unexpected mappings was higher, suggesting a very different explanation: The larger number of errors may have prompted participants to allocate more attentional resources to the task, and thus process all words and referents more deeply. However, since a recent study instead found that learning was enhanced specifically for unexpected mappings (Grimmick et al., 2019), it remains possible that prediction errors do play a role in adult word learning.

Children. More child studies are relevant to our question, but the picture that emerges from them is also mixed. Two strands of work suggest that, far from driving learning, generating incorrect expectations may hinder children's processing of new information, with negative consequences for their ability to learn this information. First, when Fitneva and Christansen (2017) asked whether 4-year-olds' word learning would benefit from encountering high proportions of unexpected mappings (as in adults), they instead found that 4-year-olds learn better when the proportion of unexpected mappings is lower. But since it is unclear whether the findings in adults demonstrate a role for prediction error, it is also unclear whether the findings in children provide evidence against it, for the same reason: The expectancy-driven effects were not item-specific.

Second, Benitez and colleagues showed that infants (Benitez & Smith, 2012) and 2-year-olds (Benitez & Saffran, 2018) learn novel word-referent associations better when the associations are demonstrated in predictable contexts, compared to unpredictable contexts. While this seems to go against the idea that prediction error boosts learning, in this task predictability was manipulated by having the referents appear in predictable or unpredictable spatial locations, but the association between the words and their referents were not themselves more or less predictable. Therefore, the prediction error signal may have enhanced memory, but for the location of the stimuli (which was not tested), rather than for the word-referent association.

In contrast, other evidence suggests that disconfirmed expectations boost children's memory. First, Stahl and Feigenson (2017) showed that 3-to-6-year-olds are more likely to remember a novel action word if the action it refers to is unexpected due to violations of physical "core knowledge" (e.g., a bag "magically" changing the color of objects that are put inside it). However, in the control condition where no expectation was violated (i.e., the object behaved "normally"), children did not learn the novel word at all (they performed at chance), likely because in this condition there was no salient action, and the very use of a novel word was thus pragmatically infelicitous. This finding suggests that perhaps the unexpected action did not boost memory because it violated an expectation, but rather because it created the pragmatic conditions for use of a novel word. Moreover, actions that violate core knowledge are not just unexpected, but outright impossible, so this conclusion may not generalize to word learning in the wild.

Second, potential evidence that children learn from disconfirmed expectations comes from Reuter, Borovsky, and Lew-Williams's (2019) eye-tracking study. Three-to-five-year-olds heard novel words while observing two potential referents, one of which was a familiar object whose name was likely known to the child, while the other was a novel (and thus nameless) object. Infants as young as 16 months (Halberda, 2003; Horst & Samuelson, 2008) reliably map a novel word unto the novel object at first exposure under these conditions, following the so-called mutual exclusivity constraint. Crucially, Reuter and colleagues embedded the novel words within sentences, and manipulated the degree of semantic constraint of such sentences, so that they would provide either a strong expectation for the name of the familiar object (high constraint) or no strong expectation (low constraint). For example, a child looking at pictures of a spoon and a novel object should generate a strong expectation of *spoon* following *Yummy! Let's eat soup. I'll stir it with a...*, whereas following *Neat! Look over there. Take a look at the…*, no strong expectation for either object should be generated.

The child then heard a novel word (e.g., …*cheem*) at the end of both high and low constraint sentences. As a result of the expectation-strength manipulation, the novel word disconfirmed a stronger prior expectation in the high than in the low constraint condition, thereby generating a larger prediction error signal in the former than the latter condition. Reuter and colleagues hypothesized that novel words associated with larger prediction errors should be better learnt, and used a preferential looking task to test this: They presented children with each novel word and two novel referents (the target, and a distractor that was the correct referent for a different novel word), and measured whether the child looked more at the correct referent than the distractor. Surprisingly, children's performance was at chance with words encountered after high-constraint sentence contexts (and instead above chance in the low constraint condition). This finding is difficult to reconcile with prediction error being the driver of children's memory: If it were, children should have been more likely to gaze at the correct referent in the high than the low constraint condition, because novel words disconfirmed a stronger prior expectation in the former than the latter condition.

Nevertheless, Reuter et al. (2019) suggested that their findings support error-driven accounts of novel word learning because they also found a positive correlation between each child's ability to revise following a disconfirmed prediction and their performance at test. Specifically, they computed a "predict-and-revise" looking measure, which was larger the more the child looked at the familiar object before hearing the novel word (i.e., the stronger their prior expectation) *and* the more they looked towards the novel object upon hearing the novel word (i.e., the faster they revised their prior expectation). They argued that a positive correlation between children's "predict-and-revise" looking pattern during learning and the extent to which they preferentially looked at the target referent for the novel word at test was evidence that the revision of incorrect expectations was driving learning. But while this correlation was specific to novel words that were embedded in high-constraint sentences (i.e., no correlation was present for items that were presented at the end of low-constraint sentences), this interpretation is at odds with the lack of an overall memory advantage for words presented in the high-constraint condition.

Thus, we suggest an alternative interpretation is more likely: High-constraint sentences may have hampered memory by shifting attention away from the novel object, and only those children who were able to recover from this attentional shift would have learned the correct referent for the novel word. In contrast, low-constraint sentences did not reduce children's preference for looking at the novel object, thus supporting memory regardless of individual differences in sentence processing ability. Importantly, under this interpretation, the relation between individual children's learning and their sentence processing ability could be entirely explained by a common underlying factor, such as processing speed, rather than being explained by a specific ability to predict-and-revise.

In sum, we do not know whether a prediction-error mechanism underlies the formation and consolidation of novel word-object associations: Theories of memory based on prediction error predict that adults and children should form stronger memory representations following the disconfirmation of stronger expectations, but the empirical evidence is inconclusive. There is evidence that children have weaker memories for novel words when they are encountered in unexpected contexts (Benitez & Smith, 2012: Benitez & Saffran, 2018), but also some suggestive evidence that strong but incorrect expectations may in fact be beneficial (Stahl & Feigenson, 2017; Reuter et al., 2019). In adults, no study has contrasted memory following a stronger than a weaker disconfirmed expectation.

Thus, our first question is whether adults acquire stronger memories for new word-object associations, if they are observed in the context of a violation of a stronger linguistic expectation. Since word learning is a lifelong process, our second question is whether the underlying mechanisms remain similar across the lifespan or whether they themselves develop, and therefore we also compare adult performance to that of 2-to-4-year-olds on the same learning task. If we find evidence that this effect emerges early in development, this would suggest that the computation of prediction errors plays a role in word learning from the early stages of language acquisition.

The current study

Using a task similar to Reuter et al. (2019), we asked whether expectation strength affects the strength of memory representations for the mapping between a novel word and its referent. Importantly, we did so both for children (2-to-4-year-olds) and young adults (university students), so we could directly observe any developmental changes in the mechanisms used for word learning (unlike Reuter et al., who tested only children). While we disagree with Reuter et al.'s interpretation of their findings, note that we do not take issue with their design, and in fact we adopt a very similar design.

Reuter et al.'s (2019) design has two key strengths. First, it allows for a comparison between disconfirmed expectations that differ in strength (of the a priori expectation): This is an ideal comparison for testing the effect of prediction errors on subsequent memory (see Greve et al., 2017). In contrast, most previous studies (Stahl & Feigenson, 2017; Benitez & Smith, 2012; Benitez & Saffran, 2018) compared confirmed to disconfirmed predictions, which is problematic because these conditions do not just differ in the magnitude of the prediction error: When a prediction is disconfirmed, the predicted but not encountered word may linger in memory (Rommers & Federmeier, 2018), and potentially counteract the benefits of a larger prediction error on memory, if it interferes with encoding of observed word. Second, expectations strength is manipulated using sentence contexts (rather than artificially, by changing word-referent mappings mid-way through the experiment, as in Fitneva & Christiansen, 2011, 2017), thus providing a more ecologically valid test. We retained both of these aspects of Reuter et al.'s (2019) study, but our procedure did differ from theirs in some important respects, which we highlight below.

Like Reuter et al. (2019), we manipulated contextual constraint in order to vary expectation strength: Adult and child learners encountered novel words (e.g., *cheem*) embedded within sentences that were either more constraining (*Now, Peppa will eat the cheem*) or less constraining (*Now, Peppa will get the cheem*) with respect to the visual context. The visual context always consisted of two objects: a familiar object that fit the more constraining verb (e.g., an apple for *eat*) and an unfamiliar object (e.g., the jelly-like object in Figure 1). Since the younger children we tested were 2-year-olds (vs. 3-year-olds in Reuter et al., 2019), we took our constraining verbs from Mani and Huettig (2012), who showed evidence for prediction in 24-month-olds.

Based on the vast literature on linguistic prediction in adults and children, we expected listeners to generate a strong expectation that the familiar object would be mentioned following an High Constraint context – because Peppa is much more likely to eat the apple than the jelly-like object in Figure 1 (as we confirmed in a post-test; see Methods below). In contrast, following the Low Constraint context, listeners could generate only a weaker expectation (or no expectation at all), because “Now, Peppa will get the…” is not as strongly predictive of “apple” as “Now, Peppa will eat the…” is.

In order to disconfirm listeners’ expectations, we relied on the presence of the unfamiliar object in the display (similarly to Reuter et al., 2019). Since even very young children prefer to map novel words onto unfamiliar (and thus nameless) objects when the alternative is a familiar object with a known name (i.e., they follow the mutual exclusivity constraint; Halberda, 2003), both children and adults should be biased to revise their expectations, and select the unfamiliar object as the referent of the novel word. This bias may not operate on 100% of trials, so sometimes participants may select the familiar object as a referent for the novel word. In such cases, it may be that participants noticed the novel word but chose to interpret it as a novel name for the familiar object (e.g., the name of a novel variety of apple), or it may be that they failed to notice the novel word (e.g., because they followed their expectations).

Because it is hard to discriminate between these two options, we conducted analyses that exclude such cases, and are restricted to instances in which participants selected the unfamiliar object explicitly, as in these cases we can be certain that they mapped the novel word onto the unfamiliar object. Crucially, while the occurrence of the novel word should disconfirm participants’ expectations following both more and less constraining contexts, the magnitude of the resulting prediction error should be larger following more constraining contexts, where the strength of the prior expectation was higher. Compare Figures 1a and 1b for a graphical illustration of the processes at play during high and low constraint learning trials.

To test how memory depends upon processing during learning, we asked participants to select a referent for each novel word at test to probe retention of the novel mappings. Note that this task differs from the preferential looking measure used by Reuter et al. (2019), and it is a more explicit measure of memory. We chose this explicit measure because it is the one used in much research on the mutual exclusivity constraint. Studies that have tested 2-year-olds on similar tasks have shown that, even though children correctly map the novel word *cheem* to the unfamiliar object on the fly, they often fail to retain the mapping established via mutual exclusivity in memory when tested at short (i.e., on the order of 5-10 minutes) retention intervals (e.g., Horst & Samuelson, 2008; see Samuelson & McMurray, 2017 for review; but cf. Spiegel & Halberda, 2011). While this means we were expecting the youngest children to perform well below ceiling overall in our explicit memory test, it also provides an additional motivation for our study: If children initially encode novel words only weakly in memory after a first encounter, is it possible to strengthen such memory traces by encouraging them to generate linguistic expectations that will be later disconfirmed?

To summarize, we hypothesize that both adults and young children should be more likely to remember novel words that violate stronger, as opposed to weaker expectations. We test this hypothesis in 7 experiments (see Table 1 for an overview).

Table 1. Overview of experiments. Please refer to the text for an explanation of the differences between experiments.

Experiment	Participants	Aim	Manipulation	Testing modality / task during break	Context repetitions
1	40 adults	Power calculation	Verb constraint	Experimenter present / tapping, conversation with experimenter	1
2	40 adults	Power calculation	Verb constraint	Online / video + comprehension questions	2
3	58 adults	Replication of Exp. 1-2	Verb constraint	Online / video + comprehension questions	1
4	58 adults	Control experiment	Object distractor	Online / video + comprehension questions	1
5	65 adults	Replication of Exp. 4	Object distractor	Online / video + comprehension questions	1
6	80 children	Child version of Exp. 1-3	Verb constraint	Experimenter present / tapping	1
7	86 children	Child version of Exp. 4-5	Object distractor	Experimenter present / tapping	1

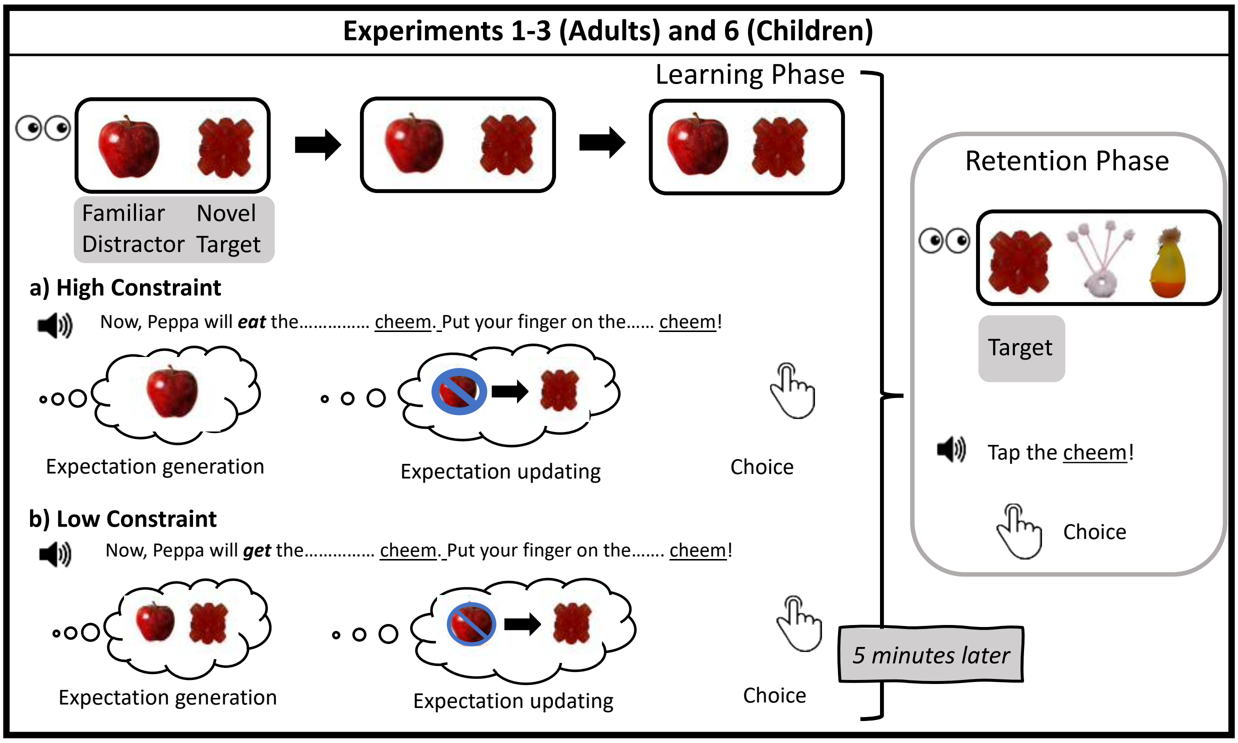
Experiments 1-3: Verb-constrained prediction errors in adults

While the paradigm was designed with children in mind, we first tested it on adult participants to assess the robustness of the effect. We established this in three experiments, which differed minimally in procedure. These differences are described below (and summarized in Table 1), but since findings were consistent across experiments, here we present combined results. All materials, data, and analyses scripts, including separate analyses and graphs for each experiment are available at https://osf.io/zvn6u/?view_only=ce8cc8f5432e41019498a98a2687982b, see Additional analyses in the *analysis_scripts* folder, section 1).

Methods.

Participants. Experiments 1 and 2 tested 40 adults each; this sample size was a rough estimate, and it was expected to yield around 80% power only with a large effect size (d=0.8; Westfall, Kenny, & Judd, 2014). We then used a simulation approach to compute sample size (N) for subsequent studies. We did this through a bootstrapping approach: we repeatedly (1000 times) randomly sampled N adult participants, analyzed retention accuracy as reported below (Data Analysis), and extracted the z statistics associated with the effect of interest (i.e., the effect of sentence constraint). We defined power as the percentage of samples that yielded z equal to or greater than 1.645 - i.e., the threshold for significance of a one-tailed test, as our prediction is directional: High Constraint contexts should lead to better memory than Low Constraint contexts. When this procedure was applied to data from Experiments 1 and 2, it indicated that 58 participants would achieve 95% power, so we recruited that many participants for a replication (Experiment 3). In total, 138 University of Edinburgh students (32 male, age range: 17 to 31; 40 participants did not provide age information) took part across the three experiments, either for course credit or £2; 16 reported to be native speakers of a language other than English, but since this did not affect the results (see Additional analyses in the *analysis_scripts* folder on the OSF, section 4), the analyses below disregard language status. The study received ethical approval from the University of Edinburgh.

Figure 1. Schematic depiction of the experimental design in Experiments 1-3 and 6, including a graphical illustration of the processes at play during different types of learning trials: a) High Constraint trials, b) Low Constraint trials. Note that in (a) we conservatively assume no expectation that the novel object will be named before the participant hears the novel word – this is because the novel objects only had a loose fit with the constraining verb (e.g., the spiky red object in the figure had a jelly-like consistency). We depict only learning trials on which participants choose the novel object as the referent of the novel word.



Materials and Procedure. The experiments consisted of two phases (see Figure 1). In the learning phase (top), participants completed 14 trials: Following two practice trials, 8 experimental trials were randomly interspersed with 4 filler trials. All learning trials had the same structure. Participants saw a picture of the cartoon character Peppa Pig centered on the top half of the screen. On the bottom half of the screen, they saw photographs of a familiar and an unfamiliar object.

Participants began a trial by clicking or tapping on the picture of Peppa Pig, which triggered a pre-recorded sentence. To test whether repetition helps participants revise a disconfirmed expectation, in Experiment 2 adults heard two sentences, so the target word was always presented at least twice. However, adults' performance in Experiment 2 did not differ from Experiment 1, where only one sentence was used. Thus, Experiment 3 and all other experiments reported here used only one sentence. Participants could listen to the sentence as many times as they wished by tapping on the top picture again.

Filler sentences were always high constraint and mentioned the predictable, familiar object (e.g., *Now, Peppa will rock the baby*) in order to encourage participants to predict familiar words. Crucially, on half the experimental trials participants listened to a High Constraint sentence (e.g., *Now, Peppa will eat the*, when the familiar object was an apple), but on the other half they listened to a Low Constraint sentence (e.g., *Now, Peppa will get the*). This way we manipulated the degree to which participants expected to hear the name of the familiar object. Constraint was manipulated within participants and items, counterbalanced across two lists.

While filler sentences always ended with the name of the familiar object, experimental sentences ended with one of 8 novel pseudowords (*cheem*, *dite*, *doop*, *fode*, *foo*, *pabe*, *roke* and *yok*), mostly drawn from Horst and Samuelson (2008). After the sentence, learners heard an instruction (e.g., *Put your finger on the cheem!*) asking them to select the object corresponding to the final word in the sentence. Unfamiliar objects were selected from Horst and Hout's (2016) NOUN database; familiarity and nameability were kept as low as possible, but such that the novel objects would always match the constraint of the verb in High Constraint sentences (e.g., the object paired with *eat* had to look edible). A post-test with 20 adults (7 males, 22 to 61 years of age) recruited from the online platform CloudFlower confirmed that novel objects were a better fit for the constraining verbs they were paired with (M = 3.08 on a 1-to-7 Likert scale), than for another (randomly selected) constraining verb (M = 2.19, $t(19) = 4.12$, $p<.001$). The same post-test showed that, unsurprisingly, familiar objects were a better fit for the constraining verbs (M = 6.10) compared to the unfamiliar objects (M = 3.08) they were paired with ($t(19) = 7.85$, $p < .001$). We return to this issue below as it was part of the motivation for conducting Experiments 4 and 5.

Following completion of the learning phase, participants took a short (approximately 5-minute-long) break. What happened during the break depended on whether the experiment was conducted in the lab or online. Participants in Experiment 1 were tested in the lab and, during the break, they first tapped on a series of cartoon characters (this task was designed for children, and is described in more detail below, as it was also used in Experiments 6 and 7); since they completed this task quite quickly, for the remaining time they engaged in a conversation with the experimenter about their studies. Participants in Experiments 2 and 3 completed the study online and, during the break, they were asked to watch a short video from an episode of Peppa Pig and answer four comprehension questions (to ensure they were paying attention).

Immediately after the break, all participants completed 8 trials in the retention phase (bottom of Figure 1). On each retention trial, they again tapped on the picture of the cartoon character Peppa Pig (top of the screen) and then heard an instruction to select the object corresponding to one of the novel words (e.g., *Tap the cheem!*), while they observed three randomly-ordered pictures at the bottom of the screen: the unfamiliar target object (the one that had appeared on the learning trial the novel word was used on) and two other unfamiliar objects, which served as distractors. Of these, one was a target object from a different trial, while the other had been also encountered by participants in the learning phase, but on a filler trial, and had therefore not been named (see Additional analyses in the *analysis_scripts* folder on the OSF, section 5, for a breakdown of participants' errors by distractor type). Across retention trials, each unfamiliar target object appeared twice (once as target, once as distractor) and each unfamiliar filler object also appeared twice (always as a distractor, but paired with two different target words). Participants never received any feedback about the accuracy of their choices. When pairing target objects with distractors, we made sure that the average pairwise dissimilarity of the three objects was comparable across trials (Mean = 0.8173, SD = 0.098, range [0.6490, 0.9624]; ratings from Horst and Hout, 2016).

All spoken instructions were recorded by a female native speaker of Scottish English with child-directed prosody. Target words were recorded separately and combined with the spoken contexts online, so that we could fully randomize object-word pairings for each participant. Trial order was also randomized separately for each participant and each phase of the experiment. Participants first completed the learning phase for all items and then completed the retention phase (i.e., learning and retention were fully blocked, with no interleaving) The task was custom-coded in HTML and Javascript. An OSF link to the code is available upon request: Since some of the visual stimuli are protected by copyright, we are unfortunately unable to make all materials publicly available.

Data Analysis and Results.

Data analysis. We analyzed participants' choices on learning trials (i.e., choosing the novel vs. familiar object) and their accuracy on retention trials as a function of Constraint. For the retention trials, accuracy was coded in terms of whether participants were able to retain the pairing of the novel label with the novel object, regardless of whether they had chosen the novel object or the familiar distractor during the learning phase. Additional analyses of retention accuracy controlled for the choice made on the corresponding learning trial (Choice-at-learning) and were followed up with separate analyses of retention trials for which the novel object had been chosen (Novel) on the corresponding learning trial, and retention trials for which the familiar object had been chosen during learning (Familiar) to check how previous referential choices affected retention. Fixed effects were contrast coded and centered.

Since we combined data for three experiments, Experiment was added as an additional factor with three levels and contrast coded; the first contrast compared performance in Experiment 1, which took place in the lab, to performance in the two online experiments (2 and 3), while the second contrast compared performance in Experiment 2 to Experiment 3. The models included interactions between these two contrasts and the fixed effect of interest (Constraint); for analyses of retention accuracy, we initially also included interactions between the Experiment contrasts and

Choice-at-learning, but these more complex models did not converge. All analyses used generalized linear mixed effects models with a logistic link function (function *glmer* from the *lme4* package; Bates, Maechler, Bolker, & Walker, 2015) in R (R, Version 3.5.1). Random effects structure was kept maximal, unless (1) correlations between random effects and/or (2) higher-order random slopes had to be dropped to aid convergence (full model specifications available in the Analysis Summary within the *analysis_scripts* folder, section 1, at the OSF link). Instead of *p* values, we report 95% confidence intervals for model estimates from the *confint* function (method="Wald").

Results. To maximize power, we report a combined analysis of data from all three adult experiments, but findings were highly consistent across all experiments (see Additional analyses in the *analysis_scripts* folder, section 1, on the OSF for separate analyses for Experiments 1, 2 and 3), and there were no significant differences between Experiments (either as main effects or interactions with Constraint) in any of the analyses reported below (see Analysis Summary in the *analysis_scripts* folder, section 1, on the OSF). Importantly, the planned replication (Experiment 3) was successful ($z = 1.65$). Descriptive statistics for these and subsequent experiments are provided in Table 2.

Accuracy on filler trials was 100%. During learning, adults were more likely to (correctly) select the novel object on low constraint (92%) than high constraint trials (81%); this difference was significant: log-odds $B = -1.59$, $SE = 0.26$, $z = -6.23$, CI = [-2.53,-1.09]. Conversely, on retention trials, adults were more accurate for novel word-object pairs they had encountered on High Constraint trials during the learning phase (76%) than on those they had encountered on Low Constraint trials (69%); log-odds $B = 0.39$, $SE = 0.15$, $z = 2.65$, CI = [0.10,0.67]; see Figure 2, top left. This pattern was qualified by an interaction between Constraint and Choice-at-learning (log-odds $B = 1.38$, $SE = 0.49$, $z = 2.81$, CI = [0.42, 2.33]), which indicated that it was driven by novel (i.e., "correct") learning trials; log-odds $B = 0.66$, $SE = 0.17$, $z = 3.98$, CI = [0.34,0.98]. In contrast, retention of familiar (i.e., "inaccurate") learning trials tended to be worse for High Constraint items, but this pattern was not reliable; CI = [-1.68,0.07].

Figure 2. Retention accuracy (%) as a function of Verb Constraint (left) or type of Object Distractor (right) and of the referent chosen during learning (Familiar vs. Novel). The top panels report data from the adult experiments (Verb Constraint: Experiments 1-3; Object Distractor: Experiments 4-5), while the bottom panels report the child data (Verb Constraint: Experiment 6; Object Distractor: Experiment 7). Conditions where weaker expectations were violated are represented by a filled circle, while conditions where stronger expectations were violated are represented by an empty circle. The error bars represent 95% bootstrap CI's (1000 samples) over subjects. The dashed horizontal lines represent chance performance (33%).

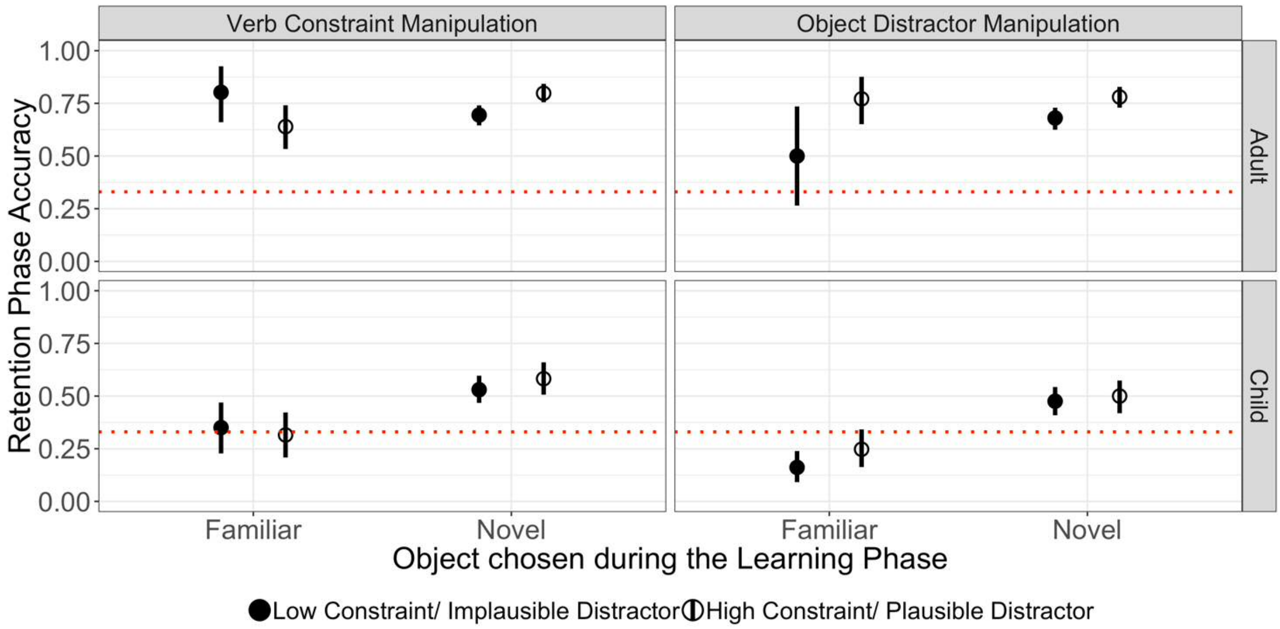


Table 2. Descriptive statistics for all experiments.

	Experiment	1-3	4-5	6	7
% Filler accuracy (learning phase)		100	>99	>99	96
% Novel object choices (learning phase)	High Constraint/ Plausible Distractor trials	81	86	66	63
	Low Constraint/Implausible Distractor trials	92	96	77	69
% Retention accuracy (novel trials)	High Constraint/ Plausible Distractor trials	80	79	57	50
	Low Constraint/Implausible Distractor trials	69	68	52	49
% Retention accuracy (familiar trials)	High Constraint/ Plausible Distractor trials	61	73	30	25
	Low Constraint/Implausible Distractor trials	78	48	35	20

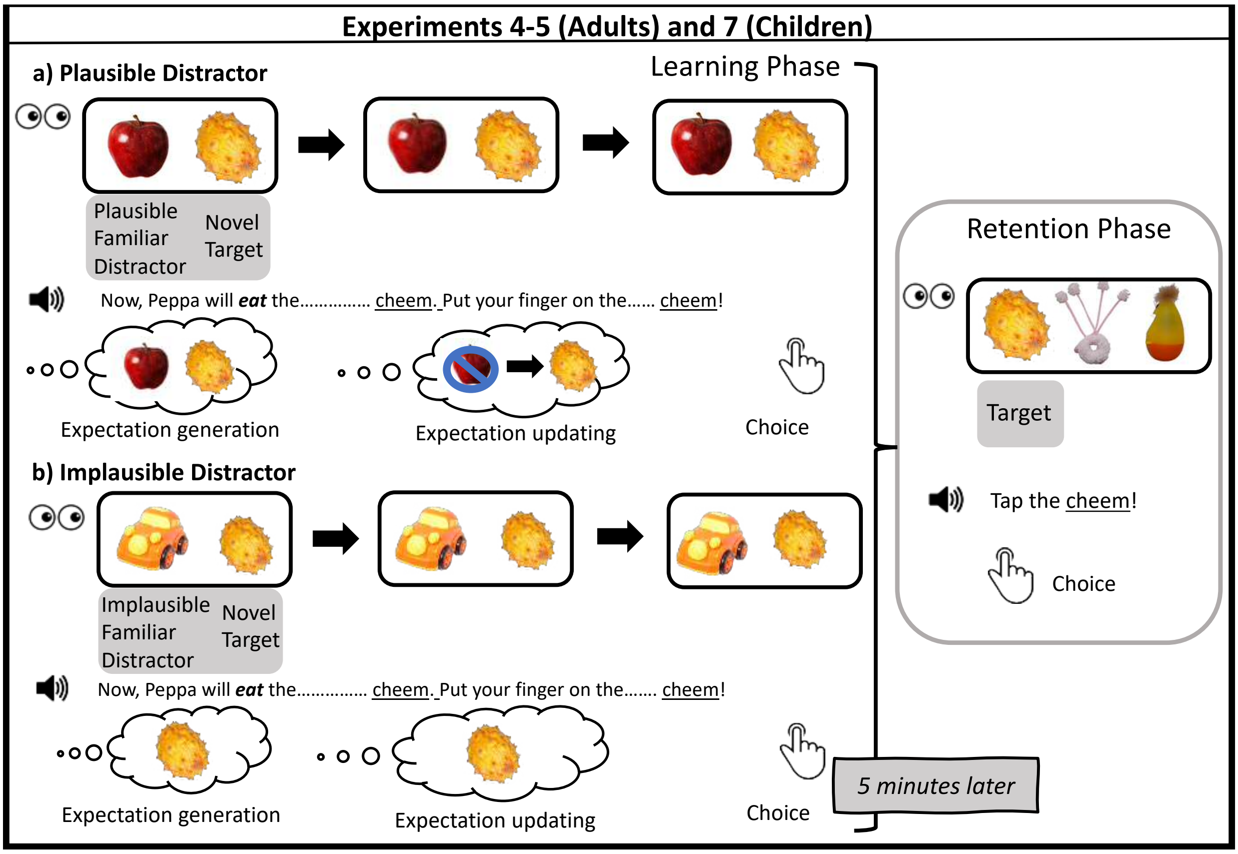
Discussion.

In accord with prediction error-based theories of memory (Henson & Gagnepain, 2010), adults were more likely to retain a newly formed association between a word and its referent when that association disconfirmed a stronger expectation compared to a weaker one. Importantly, this is not merely a novelty effect: Pseudowords and unfamiliar objects were equally novel for participants across High and Low Constraint contexts. Critically, what changed was the strength of the prior expectations generated by the verbs.

However, adults were also much more likely to disregard mutual exclusivity when the constraint was High rather than Low (e.g., picking a picture of an apple as the referent for *cheem* more often after *eat* than *get*). This may suggest that, when contextual support is strong, adult word learners may be more likely to infer that a novel word is a synonym for a highly expected familiar word (e.g., *cheem* is a synonym for *apple*, or perhaps a type of apple). While this finding is interesting in itself, and in line with previous evidence about adults' learning of novel word meanings from context (Borovsky et al., 2010), it also means that we may have underestimated the benefit of disconfirming strong expectations: Since familiar target objects were a much better fit than unfamiliar objects after High Constraint contexts, adult learners may have found it more difficult to revise their expectations following such contexts. Thus, we devised a second version of the task where new unfamiliar objects were selected to better fit the High Constraint verbs.

Importantly, the new version also addressed a potential confound. Given that High and Low Constraint conditions used different verbs, and that constraining verbs tend to be semantically richer, it is possible that adult learners performed better in the High Constraint condition simply because they could build richer and more distinctive representations for the word meanings, providing more cues for retrieving information from memory. In the new version we therefore kept sentential contexts constant and manipulated expectations by varying the plausibility of the familiar object distractor instead.

Figure 3. Schematic depiction of the experimental design and graphical illustration of the processes at play during different types of learning trials in Experiments 4-5 and 7; a) Plausible Distractor trials, b) Implausible Distractor trials. Note that in (a) the strength of the expectation is larger for the plausible familiar distractor (apple) than the novel object (exotic fruit), but there is some expectation for the latter to be named – this reflects the findings from our post-test: The novel objects used in Experiments 4-5 and 7 were less of a good fit for the constraining verbs compared to the familiar objects, but they were also a better fit compared to the novel objects used in Experiments 1-3 and 6 (cf. Figure 1). In (b) the expectation updating step confirms the expectation generated initially (i.e., that the novel object will be named). We depict only learning trials on which participants choose the novel object as the referent of the novel word.



Experiments 4 and 5: Generating prediction errors using plausible distractor objects in adults

These experiments were closely modelled on Experiments 1-3 but with two key modifications. First, we replaced all unfamiliar objects with objects that, while still unfamiliar, would better fit constraining verbs. For example, the target for *eat* was now an exotic fruit (see Figure 3; a full list of materials is available in *the materials&lists* folder on the OSF). An additional 20 adults (6 male, 19 to 57 years of age), who participated in a similar post-test to the one mentioned above, rated the new unfamiliar objects as more likely to undergo the actions referred to by the constraining verbs ($M=4.91$), compared to the unfamiliar objects used in Experiments 1-3 ($M = 3.08$, $t(34.72) = 5.40$, $p < .001$).

Secondly, learners were exposed only to semantically rich verbs (the constraining verbs from Experiments 1-3). Rather than manipulating expectations by varying the verb, we instead paired the same constraining verb (e.g., *eat*) either with a familiar object that fit its constraint (e.g., apple, as in Experiments 1-3) or with a different familiar object (e.g., car), which was implausible given the verb (see Figure 3b). Thus, if semantic richness was responsible for the memory boost we observed previously, we should now find no difference in retention accuracy using this design. However, if the memory boost was driven by disconfirmed expectations, then we should find better retention accuracy for trials with plausible than implausible familiar object distractors.

Implausible distractors should facilitate mapping of the novel word onto the correct, unfamiliar target, even before the novel word is heard, so they should make it less likely that participants will have their expectations disconfirmed (see Figure 3b); in other words, on implausible distractor trials both the sentence context and the mutual exclusivity constraint should bias participants to map the novel word onto the unfamiliar object. In contrast, on plausible distractor trials, participants should still generate a strong expectation that the plausible familiar distractors will be named (just as on high constraint trials in Experiments 1-3); in addition, they may generate a weaker expectation that the unfamiliar object will be named (as this also fits the constraint of the verb, though not as well as the familiar object). In any case, the occurrence of the novel word should disconfirm the stronger expectation for the familiar distractor to be named, generating prediction error (see Figure 3a).

Participants.

One hundred and twenty-three adult participants took part online. Fifty-eight of these were students from the University of Edinburgh (14 male, age range: 18 to 22, one participant did not provide age information), who took part in Experiment 4. The remaining 65 participants were students from Cardiff University (11 male, age range: 19 to 22, two participants did not provide age information) and they took part in Experiment 5; two participants only completed the learning phase, so analyses of retention accuracy are based on a sample size of 63 participants. Across the two experiments, eleven participants were native speakers of a language other than English (6 in Experiment 4, 5 in Experiment 5).

Methods.

The procedure was identical to Experiment 3. The design and materials were similar except for the modifications described above: New unfamiliar target objects were chosen that provided a better fit to the constraining verbs, and only sentences with constraining verbs were used, as we instead varied the identity of the familiar distractor object, which could either be a good fit for the verb (e.g., *apple* for *eat*; Plausible Distractor) or not (e.g., *car* for *eat*; Implausible Distractor).

Experiment 4 and 5 were almost identical replications of each other, with only a minor variation in the assignment of items to conditions across the two experimental lists. We used two lists in order to counterbalance the assignment of items to conditions (Plausible vs. Implausible Distractor). While analyzing Experiment 4 data, we noticed that for a subset of the items, adults were particularly likely to select the incorrect (familiar) distractor as the referent for the novel word in the Plausible Distractor condition (but not in the Implausible Distractor condition), and these items happened to cluster together in the counterbalancing (i.e., they all appeared in the Plausible Distractor condition in the same list). As a result, one list led to fewer novel object selections during the learning phase on Plausible Distractor than Implausible Distractor trials (88% vs. 99% Novel choices), while the other did not (98% vs. 96% Novel choices). Since we were concerned this may affect the results, we re-distributed item versions across lists before running Experiment 5. Lists for both experiments are available in the *materials&lists* folder on the OSF.

Results and Discussion.

Since the two experiments yielded comparable findings, here we report combined analyses to maximize power. Again, Experiment (contrast coded) and its interactions with the predictors of interest (Distractor and Choice-at-Learning) were added to all models, and again there were no significant differences between experiments, and there were no interactions modulating any of the effects reported below. For separate analyses for each experiment, see Additional analyses in the *analysis_scripts* folder, section 2, on the OSF. Accuracy on filler trials was higher than 99%. During learning, adults were more likely to (correctly) select the target when the familiar distractor was implausible (96%) compared to when it was a good fit (86%), though this difference was only marginal; log-odds $B = -1.84$, $SE = 1.10$, $z = -1.68$, CI = [-3.99,0.31].

Most importantly, adult learners performed better at retention when their expectations had been disconfirmed during learning (78%) than when they had not (67%); log-odds $B = 0.61$, $SE = 0.19$, $z = 3.43$, CI = [0.26,0.96] (and this pattern did not depend on their choice during learning; CI = [-2.22,0.49]); see Figure 2, top right. Thus, disconfirmed expectations can enhance memory for novel words, and it is unlikely that the findings from Experiments 1-3 were only due to differences in semantic richness between verbs.

Experiments 6-7: Children

Having established that adults' memory for novel word-object associations is boosted by larger prediction errors, we tested whether children would show similar effects using both the original design (i.e., manipulating verb constraint as in Experiments 1-3) and the modified design (i.e., manipulating the distractor object as in Experiments 4-5).

Methods.

Participants. A refined power calculation based on data from Experiment 1-3 (total N = 138) suggested that we may have overestimated the size of the effect in adults. This refined power analysis indicated that a sample size of N=80 would achieve 83% power, so we aimed to recruit at least 80 children per experiment. The final sample sizes were 80 in Experiment 6 and 86 in Experiment 7.

We had originally planned to test 2- and 3-year-olds because this age range sits at the intersection between research on mutual exclusivity (e.g., Horst & Samuelson, 2008) and on linguistic prediction (Borovsky et al., 2012; Mani & Huettig, 2012), but a few 4-year-olds were included (10 in Experiment 6, 13 in Experiment 7) due to recruitment constraints; additional analyses including the child's age in months did not reveal any age-related differences (see Additional analyses in the analysis-scripts folder, section 3, on the OSF), so below we report analyses that collapse across all ages. Children in Experiment 6 (M_{age} = 38 months, range = 25-56 months; 45 males, 35 females) were recruited from nurseries in the Edinburgh area, Edinburgh Zoo, a local library, and from a database of families interested in research; children in Experiment 7 (M_{age} = 38 months, range = 24-59 months; 43 males, 43 females) were recruited from nurseries in and around Cardiff, Techniquest (a science museum in Cardiff), from a database of families interested in research, or through personal contacts. Written informed consent was obtained from all caregivers and verbal assent from all children. All participants were exposed to English as one of their home languages or at nursery, and some were exposed to at least one additional language (15 in Experiment 6, 16 in Experiment 7). Children who grow up bilingual may follow the mutual exclusivity principle to a lesser extent than monolingual children (Byers-Heinlein & Werker, 2009), so we added language background as a covariate in preliminary analyses. Since no differences were found in these preliminary analyses, below we report analyses collapsing across number of languages; note that in Byers-Heinlein and Werker (2009) the largest differences were observed between monolingual and trilingual children and there were only two trilingual children in our sample.

Procedure. The procedure was as similar as possible to the adult one. Children completed the task on a touch-screen tablet. Although they were allowed to pace the task for themselves, the experimenter monitored them closely to make sure they were paying attention to the spoken instructions and, in case they appeared distracted, encouraged them to listen to the instructions again. During the break between the learning phase and the retention phase of the experiment, children completed a series of three tapping games involving known cartoon characters (as in Experiment 1); in each game, their task was to find the character named by the experimenter and "turn it" into a green tick mark by tapping on it with their finger. Experiment 6 used the same lists as Experiments 1-3 and Experiment 7 used the same lists as Experiment 4.

Results.

Children's accuracy on filler trials was high (Exp. 6: >99%, Exp. 7: 96%). Like adults, children were more likely to (correctly) select the novel object on Low Constraint than High Constraint trials; Exp. 6: 77% vs. 66%); log-odds B = -0.59, SE = 0.25, z = -2.33, CI = [-1.08,-0.09]. Numerically, they were also more likely to select the novel object when the familiar distractor was implausible; Exp. 7: 69% vs. 63%), but this difference was not reliable; CI = [-0.67,0.10].

In contrast to the adult findings, children's retention of the novel word-object mappings was unaffected by the expectations they had generated during learning (see Figure 2, bottom panels). In Experiment 6, they were as accurate for pairs they had encountered on High (48%) or Low Constraint (48%) trials; CI = [-0.35,0.30]. In Experiment 7, they were similarly accurate regardless of whether the familiar distractor fit the verb well (41%) or was implausible (40%); CI = [-0.26,0.36]. These findings held even when we restricted the analysis to items for which children had chosen the novel referent during the learning phase (Experiment 6: CI = [-0.18,0.60], Experiment 7: CI = [-0.32,0.45]).

Retention accuracy was much higher when children had (correctly) selected the novel object during learning, than when they had not (Exp. 6: 55% vs. 32%; Exp. 7: 50% vs. 23%); Experiment 6: log-odds B = 1.10, SE = 0.27, z = 4.01, CI = [0.56,1.63]; Experiment 7: log-odds B = 1.33, SE = 0.21, z = 6.44, CI = [0.92,1.73]. However, choice at learning did not interact with our manipulations.

While we set our sample size for each study using power analyses, these were based on adult data, which are likely less variable than children's. However, combined analyses of data from both Experiment 6 and 7 found no evidence for an effect of expectation strength on retention accuracy (log-odds B = 0.10, SE = 0.13, z = 0.79, CI = [-0.15,0.35]), despite their increased power. There was also no indication that performance improved within the age range tested (log-odds B = -0.001, SE = 0.007, z = -0.09, CI = [-0,015,0.014]), nor that the size of the expectation strength effect was larger for older children (log-odds B = 0.01, SE = 0.02, z = 0.99, CI =[-0.01,0.04]; see Additional analyses in the *analysis_scripts* folder, section 3, on the OSF).

Follow-up analyses combining data from all 7 experiments showed that, overall, adults' choices at learning were affected by the strength prior expectations more than children's (log-odds B = -0.94, SE =0.23, z = -4.04, CI = [-1.40,-0.48]). Importantly, these analyses also confirmed that adults' retention performance was affected by the strength prior expectations more than children's (log-odds B = 0.39, SE = 0.18, z = 2.18, CI = [0.04,0.75]).

Discussion

Unlike for adults, prediction errors did not enhance children's memory for word-referent associations. This was despite clear evidence that children can generate expectations based on the constraint of verbs even at age 2 (Mani & Huettig, 2012; recall that all of our constraining verbs were English translations of stimuli in Mani and Huettig's German study). Moreover, children clearly demonstrated sensitivity to the constraint manipulation in Experiment 6: Like adults, they were much more likely to disregard mutual exclusivity when constraint was High (i.e., picking the apple as the referent more often after *eat* than *get*), though their choices at learning were less sensitive than adults' to the strength of prior expectations. Finally, although children's memory performance was (unsurprisingly) lower than adults', it was still above chance, which suggests that, although the task was difficult, children still encoded significant amounts of information during the learning phase. Thus, our results cannot be explained by a floor effect. They suggest that prediction errors play a surprisingly small role in how children encode word meanings.

Moreover, as we discuss below, other aspects of these data may be informative for models of children's word learning. Children were strongly affected by their choices during learning: In fact, while their retention was above chance-level (33% in this task) for words they had (correctly) mapped onto the novel referent during learning, it was at chance for words they had instead mapped onto the familiar referent. This suggests that children had only tracked one potential word-referent mapping during this task (Stevens et al., 2017; Trueswell, Medina, Hafri, & Gleitman, 2013). We return to this point in the General Discussion. Finally, while Horst and Samuelson (2008) found no evidence for retention in 24-month-olds, we showed that children aged between 2 and 4 years were able to retain the new word-referent mappings at above-chance levels over at least a 5-minute period. This could suggest that children's retention abilities improve dramatically during the second year of life, but note another important difference between our design and Horst and Samuelson's: We presented the novel words in informationally rich, high constraint sentential contexts (e.g. *...eat the cheem*), which may have facilitated more robust encoding of the word-referent mappings, whereas they used only low constraint contexts (e.g., *get the cheem!*).

General Discussion

Can a prediction-error mechanism explain how adults and children encode associations between novel word forms and their meanings? The evidence around this important question is surprisingly mixed and, despite considerable evidence that both adults and children can process language predictively, the role of prediction in the creation of new linguistic representations remains poorly understood. In the introduction, we argued that a key hypothesis of error-driven accounts of memory formation is that the disconfirmation of expectations should enhance memory for the unexpected information and, importantly, the more so the stronger the initial expectation. In this study, we tested this prediction in both 2-to-4-year-olds (2 experiments, combined N = 166) and young adults (5 experiments, combined N = 259). Below, we summarize our findings and then discuss their implications for our understanding of the mechanisms that support word learning and their development.

There are two key findings. First, young adults are more likely to remember a novel word-object association that has disconfirmed a stronger, compared to a weaker, expectation. We established this finding (Experiments 1 and 2), directly replicated it (Experiment 3), and showed that it still held when we modulated expectation strength through visual rather than linguistic context (Experiments 4 and 5). Second, and in contrast to the adult findings, 2-to-4-year-olds' memory was not enhanced by violations of stronger, compared to weaker expectations (Experiments 6 and 7). This was despite the fact that children clearly generated linguistic expectations: These expectations were strong enough to affect their referential choices (i.e., choosing the familiar object more often when it was more expected). Moreover, these expectations also had an indirect effect on memory: When children failed to revise during the learning phrase, they retained nothing about the novel objects and associated labels for the test phase. But when words were mapped to novel objects during learning, expectation strength did not affect children's retention.

Prediction error shapes the encoding of linguistic information in adult memory: Implications for models of word learning.

Our adult findings clearly show that linguistic expectations shape the encoding of the link between novel words and their meanings in memory, and can thus be viewed as an extension of the PIMMS framework for memory (Henson & Gagnepain, 2010; Greve et al., 2017) to *linguistic* representations. Importantly, these findings also have far-reaching consequences for computational models of word learning. Such models have implemented a variety of different mechanisms, from associative (i.e., Hebbian) learning (e.g., Kachergis, Yu, & Shiffrin, 2012; McMurray, Horst, & Samuelson, 2012; Yu, Smith, Klein, & Shiffrin, 2007) to Bayesian inference (e.g., Xu &

Tenenbaum, 2007; Frank, Goodman, & Tenenbaum, 2009), from hypothesis testing (e.g., Stevens et al., 2017; Trueswell et al., 2013; Yu et al., 2007) to the application to semantic-interpretation rules (e.g., Siskind, 1996). However, with a few exceptions (Plaut & Kello, 1999; Ramscar et al. 2010; Grimmick et al., 2019; Stevens et al., 2017), such mechanisms have not included error-driven learning.

An error-driven learning mechanism is one that updates the current state of the model based on the discrepancy between expected and observed inputs. By doing so, it can account for the role played by prior expectations in learning: In our study, generating a stronger, but incorrect, prior expectation led to the creation of a stronger memory trace for the correct word picture-mapping (once the initial expectation was revised), suggesting that the generation of incorrect expectations may benefit word learning. It is useful to contrast this with associative (Hebbian) learning: In its simplest form, an associative word learner tracks the co-occurrences between words and referents, augmenting the strength of the association between a word and a referent every time they co-occur (e.g., Yu et al., 2007). More sophisticated associative models include parameters that let the strength of associations decay over time, and can also model attention – that is, the fact that not all possible word-referent associations are processed and stored equally (e.g., Kachergis et al., 2012).

However, associative models cannot straightforwardly account for the fact that association strength depends on prior expectations. Recall that Grimmick et al. (2019) recently showed that training adults on one set of word-referent mappings in a cross-situational learning paradigm, and then changing the mappings, led to better memory performance for the items that had been changed (i.e., initially incorrect items) than for those that had not. We argued that Grimmick et al.'s finding also supports the hypothesis that prediction error is implicated in adult word learning and, indeed, in order to reproduce their human data, Grimmick et al. augmented an associative word learning model (Kachergis et al., 2012) with a prediction-error mechanism; the associative model by itself could not reproduce their finding. Similarly, our findings suggest that adult word learning makes use of a prediction-error mechanism.

Our findings can also be explained in terms of McMurray et al.'s (2012) competition-based model of word learning. This model assumes that potential referents for a heard word compete with each other, and that this process of "in-the-moment" competition during linguistic processing can affect long-term learning (i.e., leading to changes in the weights representing the strength of associations between words and their referents). In our study, competition levels were likely higher on high-constraint and plausible distractor trials (compared to low constraint and implausible distractor trials, respectively), and thus the novel target referent had to reach a higher level of activation in order to be selected. If this higher activation translates into stronger association weights, McMurray et al.'s model could explain the higher memory performance displayed by adults for items encountered on those trials.

Note that other types of models can also be augmented with prediction-error mechanisms. Recent years have seen the emergence of so-called hypothesis-testing models of word learning (e.g., Trueswell et al., 2013). In these models, when learners hear a novel word, they generate a single hypothesis about its referent, rather than tracking all possible associations between the word and every co-occurring referent. If this hypothesis is confirmed on the next encounter, the hypothesized word-referent mapping is retained, but if it happens to be disconfirmed, then the learner needs to start afresh, as they have not retained any information from previous encounters; see Berens, Horst, and Bird (2018) for evidence supporting this model using fMRI activation patterns in the hippocampus during cross-situational word learning.

While the original hypothesis-testing model (Trueswell et al., 2013) includes processes of expectation generation and error computation, it does not incorporate a prediction-error mechanism because its learning following a disconfirmed expectation is *not* proportional to the strength of that expectation. However, a recent modification of the original model, called PURSUIT, augments it with a prediction-error mechanism where the amount of learning is proportional to expectation strength (Stevens et al., 2017). We suggest that our findings are more compatible with this augmented model than with the original hypothesis-testing model.

While an error-based learning mechanism straightforwardly explains our findings, we note that they could also be accommodated within a Bayesian framework. Expectation generation would be akin to positing a prior probability distribution, and expectations would then be updated based on how surprising the data are given the prior, to derive a posterior probability distribution. On a high constraint trial, most of the prior probability mass is placed on the expectation that the familiar object will be mentioned next, while on a low constraint trial, it is distributed more evenly between the familiar and unfamiliar object (see Figure 1). Thus, the very same data (i.e., the occurrence of the novel word) will lead to a larger updating on a high constraint than low constraint trials, because the novel word increases the probability that the unfamiliar object will be mentioned. However, existing Bayesian models of word learning (Xu & Tenenbaum, 2007; Frank, et al., 2009) do not include memory parameters, so it is unclear how they would account for the finding that larger updating leads to enhanced retention. In contrast, this finding highlights the importance of building models of word learning that account for the nature of memory.

More speculatively, our findings may also help link computational models of word learning with the cognitive neuroscience of word learning. A large body of evidence implicates the hippocampus in the initial stages of word learning in adults (Davis & Gaskell, 2009; Tagarelli, Shattuck, Turkeltaub, & Ullman, 2019; Berens et al., 2018). According to the complementary systems account of word learning (Lindsay & Gaskell, 2010), the hippocampus supports rapid, initial acquisition of novel words, whereas the neocortex is responsible for slower consolidation, typically following periods of sleep (see McClelland, McNaughton, & O'Reilly, 1995 for detailed theoretical arguments in support of the complementary systems account of learning and memory). Strong evidence for this account comes from the inability of patients with hippocampal lesions to learn new words (see Cooper, Greve, & Henson, 2019, for a recent review and discussion).

Interestingly, the hippocampus is sensitive to novelty and unexpected events (e.g., Kumaran & Maguire, 2006), and it is thought to encode not just episodic memories but also predictions about future outcomes (e.g., Shohamy & Adcock, 2010). Our finding that prediction errors affect word learning in adults, therefore, is consistent with a key role for the hippocampus in this process. Given we did not find evidence for a role of prediction error in children word learning, an interesting question for future research is whether there are significant developmental changes in the reliance of word learning processes on the hippocampus (similarly to what has been shown for other areas of cognitive development; Qin et al., 2014). It may also be that children only show sensitivity to prediction error after a period of sleep consolidation (which was not included in our study).

Do the mechanisms of word learning change across the lifespan?

A key contribution of our study is to highlight a potential developmental discontinuity in the mechanisms of word learning: While adult memory for novel word-referent mappings was affected by the strength of prior expectations, we found no evidence that 2-to-4-year-olds' memory was similarly affected. This raises the possibility that the above-described models of word learning, which have often been evaluated based on adult data, may not automatically generalize to explain children's behavior.

Our study is not the first to highlight differences between adults' and children's word learning mechanisms. We have already mentioned Fitneva and Christiansen's (2017) work, showing that 4-year-olds learn more when their expectations are confirmed, but adults learn more when they are exposed to a higher proportion of unexpected word-referent mappings. But while their findings suggest that children should benefit from generating correct expectations (see also Benitez & Saffran, 2012, 2018), we found no difference in memory performance between trials on which generating an incorrect expectation was more likely (high constraint) and those in which it was less likely (low constraint).

Can Fitneva and Christiansen's (2017) findings be reconciled with ours? Incorrect expectations may both hinder selection of the correct novel referent and benefit memory for it, if it is selected. However, when we excluded all trials on which children (incorrectly) selected the familiar referent, we still found no evidence for a difference in children's memory performance between strong and weak expectation trials. Thus, it seems more likely that children at this age are yet to develop the mechanism that makes memory sensitive to expectation strength.

Further, our results seem incompatible with Ramscar, Dye, and Klein (2013a), who argued that children's word learning is more likely than adults' to be driven by an error-based mechanism (rather than *less* likely, as our findings suggest). They devised a word learning task in which a learner driven only by prediction error (Rescorla & Wagner, 1972; Ramscar et al., 2010) would behave differently from one who additionally makes use of explicit inferences (e.g., reasoning by exclusion). Participants were first exposed to three novel objects and two novel words. Two of the objects co-occurred with only one of the words each, while the third object co-occurred with both of the words. When children were presented with a third novel word at test (here, *wug*), they were less likely to select this third object as a referent for *wug*. While none of the objects had co-occurred with *wug* during the learning phase, the object that had co-occurred with two other words was the least predictive of *wug*, and so it should be the least preferred choice of an error-driven learner (Ramscar et al., 2010). In contrast, adults were more likely to select the third object than either of the other objects, suggesting that they were more likely to explicitly reason by exclusion, choosing the third object because they had already mapped each of the other two objects onto the word it had co-occurred with.

While Ramscar et al.'s (2013a) findings suggest that child word learners track co-occurrence information across multiple encounters, we note that in our study co-occurrence information was identical across high and low constraint conditions. Instead, what (likely) changed across conditions was participants' processing of the novel word and novel target object; for example, by violating a strong linguistic expectation, we may have prompted deeper processing of the novel word and object, which in turn would have led to enhanced encoding of the association between word and object in memory.

We thus suggest that by the age of 4 children may be capable of accumulating information using an error-driven learning rule to track which words and referents co-occur and which do not (in accordance with Ramscar et al., 2013a), and form expectations about future co-occurrences. But at this age the violation of such prior expectations does not yet lead to deeper processing and encoding of unexpected information in memory. In sum, different mechanisms, with different developmental trajectories, may underly our ability to track regularities in the environment (i.e., statistical learning; Yu & Smith, 2007) and to focus attention and cognitive resources on the encoding of unexpected events.

The effect of linguistic prediction on children's word learning.

Our findings suggest two conclusions about how prediction affects children's learning. The first conclusion is that children's predictions affect what children learn, by guiding their attention, but the second conclusion is that these predictions do not affect the strength of children's memory representations. These two conclusions may seem to contradict one another, but we propose they can be reconciled with one another, and with findings from previous work (Reuter et al., 2019) by carefully distinguishing the mechanisms involved.

First, the predictive strength of the sentence contexts affected the inferences that children made about the likely referent of the novel word: They were more likely to choose the familiar object (thus disregarding the mutual exclusivity constraint) when the sentence context led them to expect a reference to this object. In turn, choosing the familiar object as the referent led to chance performance at test, suggesting that children's attention was focused on the selected referent, to the extent that little information about the unselected referent was retained – a finding which, incidentally, replicates previous studies (Aravind et al., 2018; Woodard, Gleitman, & Trueswell, 2016; but see Yurovsky & Frank, 2015) and is consistent with hypothesis-testing models of word learning (Trueswell et al., 2013). Importantly, however, during the learning phase children still selected the novel referent at above-chance rates, even when doing so required them to abandon a prior expectation, and when they did select the novel referent during learning, they then demonstrated above-chance retention of the association between the novel word and this novel referent during the test phase. Thus, children were capable of revising and updating their expectations based on the mismatch between those and the auditory input (i.e., when a novel word occurred instead of the expected familiar one) on the majority of trials.

Second, the predictive strength of the sentence contexts did not affect children's likelihood of retaining the association between the novel word and the novel object. Thus, while the ability to revise disconfirmed expectations may guide children to discover new linguistic information (i.e., one aspect of learning), we suggest it is not a key driver of *retention* of this information. This interpretation allows our data to be reconciled with Reuter et al.'s (2019) finding that children who show a stronger predict-and-revise looking pattern are also better at word learning. Recall that in their study children's performance at test was no greater in the high than the low constraint condition (in fact, it was greater in the latter than the former), so they also found no evidence that stronger expectations were associated with enhanced memory, when disconfirmed. What they did find was that children who engaged less in prediction-and-revision were less likely to remember high-constraint words, which is actually in line with our findings: When children did not engage in mutual exclusivity reasoning during learning, then they had poor memory at test. Thus, Reuter et al.'s findings concur with ours in suggesting that prediction-and-revision skills help reference resolution in children, but do not affect retention, so long as reference is resolved to the object that is later tested for retention.

There is however one caveat to these conclusions that is worth considering. Children's choices during learning were less sensitive to the strength of prior expectations compared to adults'. This could be in part because children's choices are often noisier than adults' (e.g., due to lapses in attention). But it is also expected because studies that have compared predictive skills between children and adults have typically found stronger effects of prediction in adults (e.g., Gambi et al., 2016, 2018; Borovsky et al., 2012). Moreover, the strength of prediction effects increases throughout the pre-school years (Gambi, Jindal, Sharpe, Pickering, & Rabagliati, in press). This raises the possibility that prediction did not affect children's retention because they did not generate expectations that were strong or consistent enough (unlike adults).

However, we think that this possibility is unlikely, because children clearly generated quite strong expectations. As noted above, when children did follow their expectations and chose the familiar referent (which they were more likely to do than adults in the High Constraint/Plausible Distractor conditions; compare 66% novel referent selections in Experiment 6 and 63% in Experiment 7 for children with 81% in Experiments 1-3 and 86% in Experiments 4-5 for adults), this choice had a large impact on their memory performance during the retention phase. Similarly, there may be a worry that the lack of expectation strength effects on children's memory is down to the task being too difficult for children of this age, but as noted above children's performance was well above chance when they selected the novel object during learning, which they did on most trials.

In sum, we argue that, despite the use of different tasks during the learning phase and different measures of learning (looking-while-listening vs. referent selection), as well as a slightly different age range (3-to-5 vs. 2-to-4-year-olds), Reuter et al.'s (2019) findings are consistent with our own: Both studies suggest that children's predictions affect reference resolution but are unlikely to drive retention of new word-meaning mappings. Therefore, we disagree with Reuter et al.'s suggestion that their findings show that children's memory for novel word-object associations is supported by a prediction-error mechanism. Instead, we suggest that children who exhibited a stronger predict-and-revise pattern were better at word learning in their study because they were faster at processing sentences, and their higher processing speed allowed them to learn following high-constraint sentences even though these initially biased their attention towards the incorrect referent.

Why did disconfirmed expectations not boost memory in young children?

If pre-school aged children can generate linguistic expectations, and revise such expectations "in-the-moment" when they are disconfirmed, then why does prediction error not affect encoding of novel linguistic information in young children's memory? Below we discuss two possible answers to this question.

One possibility is that the null effect follows from children's lack of fluency at completing the task, which follows from a recent proposal that violations of expectations only influence memory once inhibitory control skills are well-developed (Brod, Breitwieser, Hasselhorn, & Bunge, 2019). In our task, inhibitory control skills would be important for quickly suppressing the generated expectation once a novel word is encountered, allowing fluent mapping to the correct referent. Brod and colleagues (2019) have proposed that this use of inhibitory control is still not apparent even in late childhood: They found that violating expectations did not enhance memory for new declarative knowledge in children aged 9 to 12 years, but that it did enhance memory in adults (Brod, Hasselhorn, & Bunge, 2018).

This could potentially explain children's difficulty with our task. While our child participants were able to inhibit selection of the strongly expected familiar object on the majority of trials, it is likely that they took longer than adults to focus attention on the novel object, by which time, activation of the novel word in their working memory may have already started to decay, and this could have led to a weaker binding of the word-object association. In sum, perhaps children were not able to re-direct their attention quickly enough to benefit from the stronger encoding of information following a larger prediction error. If this is the case, then our findings indicate that children may have already developed an error-based learning mechanism, but their memory for novel word-referent mappings does not benefit from this mechanism (at least in our paradigm) because of delays in children's development of attentional skills.

Alternatively, children may show relative insensitivity to disconfirmed expectations because doing so is in fact adaptive for their learning. Since children's linguistic knowledge is so limited, their linguistic input is likely to deliver more surprises more frequently (i.e., unexpected words), at least compared to adults. Children may therefore be more likely than adults to "expect the unexpected" (i.e., placing a higher likelihood on the eventuality of encountering unexpected words). While this means that unexpected words may not leave a particularly strong trace in children's memory, it also allows attentional resources to be distributed more evenly across many mildly surprising words. This idea is supported by evidence that children are indeed sensitive to the predictability of the environment. For example, the so-called Goldilocks effect shows that infants and young children prefer to attend to input that is of intermediate predictability, neither too predictable nor too unpredictable given their current knowledge about the environment (Kidd, Piantadosi, & Aslin, 2014), and children can also quickly learn to expect the unexpected when they have been exposed to a speaker that talks about very unlikely events (Yurovsky, Case, & Frank, 2017).

We do not know of any research that shows that children's memory becomes more sensitive to unpredictable information as they become more knowledgeable about the environment, but if children's word learning does indeed benefit from encountering unexpected information that violates "core knowledge" (Stahl & Feigenson, 2017), this may suggest that children's memory is more sensitive to unpredictable information in domains that the child is more knowledgeable about (because core knowledge is acquired very early on). Similarly, children may be more sensitive to prediction error when there is a conflict between internally-generated expectations and strong external cues (e.g., unambiguous referential cues, such as an adult's pointing) compared to situations where there is a conflict between internally-generated expectations and the child's preferred interpretation of a novel stimulus, as in our task. In the latter case, the error signal may be too weak or noisy because it is based on the child's own developing knowledge of language, whereas strong error signals from the environment may play a much more important role in shaping children's error-based learning.

Conclusion

In sum, we showed that prediction error drives the encoding of novel word-object associations in adult memory, as associations were encoded more strongly when they violated a stronger compared to a weaker prior expectation. However, we found no effect of disconfirming a stronger versus weaker prior expectation on children's memory. The adult findings represent a clear demonstration that at least one of the mechanisms underlying adult word learning is based on the computation of prediction errors. Thus, they set an important constraint on models of adult word learning. The lack of a comparable effect of prediction error on children memory was not due to children's inability to generate linguistic expectations, nor to an inability to revise them when they proved incorrect. Instead, we suggest that children are either too slow to inhibit disconfirmed expectations or that they do not prioritize the processing of unexpected information as much as adults, because the environment is overall more unpredictable to them. These findings thus highlight an important developmental discontinuity in the mechanisms that underlie prediction's role in language learning.

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