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Predict and redirect: Prediction errors support children's word learning

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Abstract

According to prediction-based learning theories, erroneous predictions support learning. However, empirical evidence for a relation between prediction error and children's language learning is currently lacking. Here we investigated whether and how prediction errors influence children's learning of novel words. We hypothesized that word learning would vary as a function of two factors: the extent to which children generate predictions, and the extent to which children redirect attention in response to errors. Children were tested in a novel word learning task, which used eye tracking to measure (1) real-time semantic predictions to familiar referents, (2) attention redirection following prediction errors, and (3) learning of novel referents. Results indicated that predictions *and* prediction errors interdependently supported novel word learning, via children's efficient redirection of attention. This study provides a developmental evaluation of prediction-based theories and suggests that erroneous predictions play a mechanistic role in children's language learning.

Keywords

prediction; prediction error; language processing efficiency; attention

Numerous psycholinguistic theories propose that prediction supports language processing and learning (Chang, Dell, & Bock, 2006; Christiansen & Chater, 2016; Dell & Chang, 2014; Elman, 1990; Pickering & Garrod, 2013). First, learners anticipate upcoming input during real-time language processing. Then, predictions prove to be either correct or incorrect. By facilitating both confirmation of correct predictions and attention to incorrect predictions, prediction kills two birds with one stapler. As in this butchered idiom, a mismatch between the predicted input (stone) and the actual input (stapler) allows learners to consider novel input and potentially update internal representations. However, when there is a match between predicted and actual input, learners reinforce their internal representations, process predicted representations more efficiently, and devote attention to novel information that may arise later (Chang et al., 2006; Fernald et al., 2008). In sum, according to prediction-based theories, prediction supports language learning via multiple routes, regardless of the accuracy of the learner's initial predictions.

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Yet, given the rapid pace and frequent ambiguity of spoken language, is prediction a viable learning mechanism? Two lines of research suggest that this is the case. First, numerous studies demonstrate that children can predict upcoming information during language processing (Borovsky, Elman, & Fernald, 2012; Borovsky & Creel, 2014; Byers-Heinlein, Morin-Lessard, & Lew-Williams, 2017; Fernald et al., 2008; Fernald, Thorpe, & Marchman, 2010; Kidd, White, & Aslin, 2011; Lew-Williams & Fernald, 2007; Lukyanenko & Fisher, 2016; Mani & Huettig, 2012; Mani & Huettig, 2014). Second, correlational findings indicate a positive link between prediction and learning, such that children who predict more effectively while processing language tend to have larger vocabularies (Borovsky, et al., 2012; Borovsky & Creel, 2014; Lew-Williams & Fernald, 2007; Mani & Huettig, 2012). Together, these findings are consistent with prediction-based theories: If prediction is a learning mechanism, then it should be apparent in early development, and differences in prediction should correspond to differences in learning outcomes. However, these correlational findings have interpretational limits. It is possible that prediction drives learning, yet it is also possible that prediction is a consequence, not a cause, of vocabulary growth (see Rabagliati, Gambi, & Pickering, 2016 for review). Existing research is therefore insufficient to validate prediction's role in language learning.

In addition to determining *whether* prediction supports learning, empirical research must determine *how* prediction supports learning. As described above, there are at least two pathways from prediction to learning, according to prediction-based theories. First, prediction facilitates learning via correct predictions. Predicted sounds, words, and sentences are processed more efficiently, providing the learner with more time to attend to novel information that occurs later in the speech stream. Empirical findings provide some support for this view. Fernald and colleagues (2008), using sentences such as "*There's a blue cup on the deebo*", found that children's efficiency in processing adjectives and nouns (e.g., *blue* and *cup*) was related to their success in learning subsequent novel words (e.g., *deebo*). Thus, efficient and accurate predictions may support development by giving the learner extra time to encode new information, and may be inherently rewarding to the learner (Rescorla & Wagner, 1972; Schultz, 2001).

A second way that prediction may facilitate learning is via incorrect predictions. Although incorrect predictions temporarily derail language processing, learners could use the resulting prediction error to update existing language representations and optimize subsequent behavior. As with correct predictions, attention is likely to play a role, and previous evidence suggests that redirecting attention in response to a prediction error may support learning. Brooks and Lew-Williams (under review), using overtly misleading sentences such as *"Choo choo! Here comes the cow!"* in an eye-tracking task, found that children robustly predicted the expected referent (e.g., *train*), but upon hearing the unexpected noun (e.g., *cow*), children varied in how quickly they redirected attention to the unexpected referent. Importantly, the speed with which children *re*directed attention correlated positively with vocabulary size. Thus, prior findings suggest that children's abilities to generate predictions and, critically, to redirect attention when conflicting information arrives may combine to influence learning outcomes.

In the present study, we aimed to understand if and how prediction facilitates novel word learning. In order to evaluate prediction error, attention redirection, and learning within a single task, we used a novel eye-tracking paradigm and assessed moment-to-moment attention to expected and unexpected referents. Specifically, we capitalize on the child's gaze as a running index of attention and (pre)activation of semantic meaning using established eye-tracking procedures (e.g., Fernald et al., 2008; Huettig, Rommers & Meyer, 2011). By taking a time-locked measure of gaze with respect to unfolding speech (*The boy eats the…*), numerous researchers have found that children can successfully predict the unspoken, semantically related object (CAKE) before it is spoken (e.g., Mani & Huettig, 2012). Our experiment builds on this paradigm to measure how prediction might influence learning when an unexpected, but semantically related novel item appears instead.

The experiment included six independent blocks of trials, each testing the learning of a different pair of novel words. In the learning phase of each block, children saw familiar and novel referents and heard either semantically constrained or unconstrained sentences. Constrained sentences provided semantic cues to a familiar word (e.g., *"Yummy! Let's eat soup. I'm going to stir it with a…"*), but half of the sentences ended with an unexpected novel word (e.g., *cheem* instead of *spoon*). This design therefore created opportunity for prediction error: If children used semantic cues to predict a familiar word, hearing a novel word should cause a prediction error. This design also allowed us to evaluate attention redirection: If children were predicting and looking to a familiar word, they should redirect attention to the novel referent upon hearing a novel word. Thus, *constrained* sentences allowed us to measure prediction error and attention redirection, whereas *unconstrained* sentences allowed us to measure children's baseline looking preferences for novel and familiar referents in the absence of semantic cues (e.g., *"Neat! Look over there. Take a look at the spoon/cheem"*). In each test phase, children saw a pair of novel referents, and we measured children's recognition of novel words. Individual differences in looking behavior during the learning phases were compared to children's accuracy in the test phases. In particular, the constrained learning context allowed us to evaluate the hypothesis that prediction error and attention redirection jointly shape children's word learning. We expected that children would use semantic cues to predict a familiar referent, but, upon experiencing a prediction error, would vary in how they redirected attention to a novel referent.

Method

Participants

Participants were 56 children (28 male) from monolingual English-speaking households. Children were 3 to 5 years of age (M = 54 months, SD = 10.7 months). We tested 16 three-year-olds (M = 40 months, SD = 3.3 months), 20 four-year-olds, (M = 54.2 months, SD = 3.3 months), and 20 five-year-olds (M = 65.6 months, SD = 3 months). Children had no known hearing or vision impairments. We tested an additional 8 children but excluded them from analyses due to failure to complete the eye-tracking task (7), or vision impairment (1). The [name of university omitted for blind review] Institutional Review Board approved this

research protocol (Language Learning: Sounds, Words, and Grammar; IRB record number 0000007117), and a legal guardian provided informed consent for each child.

Stimuli

Visual stimuli consisted of 12 familiar objects: *spoon, truck, ball, flower, crayon, coat, guitar, phone, sandwich, door, apple,* and *kite.* Each familiar object was paired with one of 12 novel objects: *cheem, fep, gub, kaki, toma, juff, blicket, lort, manju, pisk, deebo,* and *sprock.* Novel objects were intended as functional matches for familiar objects. For example, the familiar object *spoon* and the novel object *cheem* shared functional features (i.e., a handle and a rounded base). All objects were placed on a 400×400 pixel white background, such that each subtended a visual angle of approximately 11.9° horizontal by 12.5° vertical in participants' visual fields.

Auditory stimuli in each learning phase included two types of sentences: constrained and unconstrained. Constrained sentences were intended to enable predictions to the familiar target using multiple semantic cues (e.g., *"Yummy! Let's eat soup. I'll stir it with a spoon/cheem"*). Unconstrained sentences were designed as a baseline measure of looking behavior in the absence of predictive cues (e.g., *"Neat! Look over there. Take a look at the spoon/cheem"*). Test sentences were designed to test children's recognition of words (e.g., "*Where's the…?"* or "*Find the…*"). See Appendix for a list of all auditory stimuli.

A female, native speaker of English recorded all auditory stimuli using child-directed intonation. We controlled the overall duration of the carrier frame and the target word in learning sentences. We first measured the mean length of carrier phrases and target words, and then used Praat (Boersma & Weenink, 2017) to match each sentence to the overall mean. Carrier frames were 2497 ms and target words were 514 ms, thus each sentence was 3011 ms in length. Using an identical norming procedure as in the learning phase, each test sentence duration was adjusted to 1093 ms, with a carrier frame duration of 531 ms and a target word duration of 562 ms. Finally, we used Praat to modify each auditory stimulus to a standard mean intensity of 70 dB.

There were six blocks of trials. Three blocks included only constrained sentences, and three included only unconstrained sentences. Each block consisted of four learning trials followed by four test trials (Figure 1). Within the four learning trials of a single block, children saw two familiar-novel object pairs (e.g., *spoon* and *cheem*; *truck* and *fep*). Each pair appeared on two learning trials, once with a sentence that ended with a familiar noun (e.g., *spoon*), and once with a sentence that ended with a novel noun (e.g., *cheem*). Then, four test trials assessed children's recognition of both familiar and novel objects. On test trials within a single block, children saw the familiar objects paired with each other twice (e.g., *spoon* and *truck*) and the novel objects paired with each other twice (e.g., *cheem* and *fep*), and heard simple sentences referring to one of the objects, as described above. Each of the four objects was referenced once during the four test trials. Thus, across the six blocks of trials, children viewed a total of 12 familiar objects and 12 novel objects.

Trials appeared in one of four quasi-randomized orders, such that references to familiar objects never occurred more than three times in a row, and target side (left vs. right) was

counterbalanced. A constrained block occurred first for all children. Sentence frames used on test trials were counterbalanced across blocks, and a single block always used one sentence frame (either *"Where's the…"* or *"Find the…"*). One filler trial occurred between each block. Filler trials consisted of a cartoon image (e.g., a smiley face) and a positive statement (e.g., *"How exciting! You're doing great."*). All study materials are available in Supplementary Materials.

Procedure

The study took place in a sound-attenuated room. Children sat on their caregiver's lap or on a chair with a booster seat, approximately 50 cm from an EyeLink 1000 Plus eye-tracker. Caregivers wore a visor over their eyes to prevent them from influencing their child's behavior. Children wore a target sticker on their face to allow the eye-tracker to measure eye movements.

The experimenter controlled the eye-tracking task from a Mac host computer, using EyeLink Experiment Builder software (SR Research, Mississauga, Ontario, Canada). Before beginning the task, the experimenter calibrated the eye-tracker for each child with a standard 5-point calibration procedure. During the task, children viewed stimuli on a 17-inch LCD monitor and the eye-tracker, sampling at 500 Hz, remotely and automatically recorded children's eye movements. The total duration of the eye-tracking task was five minutes and 30 seconds, on average. Immediately after the eye-tracking task, the experimenter assessed children's receptive vocabulary by administering the Peabody Picture Vocabulary Test (PPVT-IV; Dunn & Dunn, 2007).

Results

On both learning and test trials, we identified looks to the target and distractor referents within the 400×400 pixel background of each image. Prior to analyses, we identified samples in which participants' gaze location was not within these regions (i.e., track-loss). Trials were excluded if participants had track-loss for more than 40% of samples on a given trial, as in prior eye-tracking studies (Choi & Trueswell, 2010; Woodard, Pozzan & Trueswell, 2016). This criterion eliminated 11% of trials (301 out of 2688). Next, we aggregated samples into 100-ms time bins during sentences (0–4000 ms). Then, within each bin, we calculated the proportion of looks to the target referent (i.e., samples to the target referent divided by total samples to the target and distractor referents). Finally, we summarized the proportion of target looks over time in the learning phase and test phase, by subjects and by items. We used R software (version 3.5.0) for all analyses.

Our primary hypothesis was that prediction errors, coupled with redirection of visual attention, support children's novel word learning. If this is the case, we expected that children who predicted the familiar referent, and then turned (or 'redirected') their visual attention toward the novel referent once it was named, would subsequently be more successful at retaining novel word-object mappings. Therefore, we evaluated whether patterns of looking behavior in the constrained learning context were related to learning outcomes. In particular, we evaluated the degree to which a *predict-and-redirect* looking pattern on learning trials was correlated with accuracy on test trials. We operationalized the

predict-and-redirect looking pattern on learning trials as a difference score: looks to the novel referent *after* target noun onset (2800–4000 ms from sentence onset) minus looks to the novel referent *before* target noun onset (300–2700 ms from sentence onset). Thus, children with larger difference scores were those who used semantic cues to predict the familiar referent, and also redirected attention to the novel referent upon hearing the novel label. Children with lower difference scores or negative differences were those who exhibited other looking behaviors (e.g., looking to the novel referent throughout the trial). On test trials, we operationalized *test accuracy* as looks to the target referent after the target noun onset (900–4000 ms from sentence onset). We adjusted all time windows by 300 ms from target noun onset to account for the time needed to generate a saccade (Matin, Shao & Boff, 1993). For each analysis, participants were excluded if they did not contribute data to both learning phase and test phase measures (due to track-loss), or if their learning phase or test phase measures fell outside 2 standard deviations from the mean for each measure (e.g., prediction during the learning phase and test accuracy during the test phase). See Supplementary Materials for details on exclusions for each analysis.

As expected, we found that the predict-and-redirect looking pattern during learning trials significantly correlated with children's test accuracy ($r(46)=0.43$, $p=0.003$), with a moderate effect size. Children who initially predicted the familiar referent and then redirected attention to the novel referent showed greater accuracy at test (Figure 2). A power analysis confirmed that, given our sample size ($n=48$) we had adequate power to detect our primary effect of interest (87%). We also evaluated a number of alternative possibilities for this observed relation. First, we evaluated whether prediction of the familiar referent was the driving force behind the predict-and-redirect correlation. That is, we wanted to evaluate whether initially predicting the familiar referent, regardless of subsequent looking behavior, might be independently correlated with test accuracy. To the contrary, we found that looking behavior before noun onset (300–2700 ms from sentence onset) did not relate to test accuracy ($r(45)=0.12$, $p=0.43$). Next, we evaluated whether attention after noun onset was the driving force behind the observed predict-and-redirect correlation. That is, looking to the novel target once it is named may be independently correlated with test accuracy, *regardless of prior looking behavior*. Again, we found that looking behavior after noun onset (2800–4000 ms from sentence onset) did not relate to test accuracy ($r(46)=0.17$, $p=0.24$). Together, these results suggest that children's looking behaviors both before and after the onset of the novel word jointly influenced learning, but neither factor alone was independently correlated with differences in learning outcomes. Finally, we assessed whether overall looking to the novel target during learning might influence learning outcomes. That is, we asked whether the extent to which children focused on the novel object during learning – essentially ignoring the semantic cues of the constrained learning context – might be correlated with their learning outcomes. Again, to the contrary, we found that overall looking to the novel target during learning (0–4000 ms from sentence onset) did not relate to test accuracy ($r(45)=0.19$, $p=0.19$). Overall, these results suggest that a particular pattern of looking behavior – predicting a known referent coupled with redirecting attention to a novel referent – was beneficial for learning novel words.

To evaluate potential developmental changes in the constrained condition, we conducted exploratory correlational analyses, evaluating three-, four-, and five-year-old children

separately. While *r*-values were similar across the three age groups, suggesting a moderate effect size, only the data for four-year-olds reached statistical significance (three-year-olds: $r(13)=0.49$, $p=0.058$; four-year-olds: $r(17)=0.46$, $p=0.047$; five-year-olds: $r(12)=0.40$, $p=0.16$). Overall, the observed relation between a predict-and-redirect looking pattern and greater success in learning novel words may have been driven by younger children, particularly four-year-olds (Figure 2). However, given the small sample sizes within each age group and the exploratory nature of these analyses, these results should be interpreted with caution. For additional exploratory analyses by age group, see Supplementary Materials.

Next, we completed identical analyses for the unconstrained condition. Whereas the constrained condition allowed us to measure prediction error and attention redirection, the unconstrained condition allowed us to measure variation in children's looking behavior without semantic cues. If children's patterns of looking behavior were driven by the available semantic cues in the constrained condition, then we expected to observe a different pattern of findings in the unconstrained condition. Importantly, the same looking behaviors from the constrained condition were possible in the unconstrained condition: Children could look continuously to the familiar referent, look continuously to the novel referent, or shift between the familiar and novel referents. We found none of the significant effects observed in the constrained condition: There were no significant correlations between test accuracy and a predict-and-redirect looking pattern ($r(43)=-0.12$, $p=0.42$), looks to the novel target before the onset of the target noun ($r(41)=0.21$, $p=0.17$), looks to the novel target after the onset of the target noun ($r(43)=0.02$, $p=0.87$), or overall looks to the novel target ($r(42)=0.17$, $p=0.26$). As with the constrained condition, we also completed exploratory analyses by age, and found that a predict-and-redirect pattern of looking behavior during learning was not related to test accuracy within any age group (three-year-olds: $r(11)=-0.32$, $p=0.29$; four-year-olds: $r(14)=-0.40$, $p=0.12$; five-year-olds: $r(14)=0.09$, $p=0.73$). Thus, as expected, the absence of semantic cues in the unconstrained condition prevented the benefits of the predict-and-redirect looking behavior, even when children performed the same behavioral sequence as in the constrained condition (Figure 3).

Visual inspection of the data indicated substantial variation in children's learning outcomes (Figure 2; Figure 3) and marginal learning outcomes at the group level. We therefore completed additional analyses to evaluate children's test accuracy. One-sample *t*-tests indicated that children's overall test accuracy (over both conditions) was significantly greater than chance, suggesting that they were able to learn novel words (one-sample $t(55)=2.28$, $p=0.013$). Children's test accuracy for the constrained learning condition did not significantly differ from chance, suggesting that individual differences in the dynamics of looking behaviors during the learning phase were key to understanding word learning (one-sample $t(53)=-0.41$, $p=0.658$). Children's test accuracy for the unconstrained learning condition was significantly greater than chance (one-sample $t(50)=3.38$, $p=0.001$), which we return to below. Finally, a paired-sample *t*-test indicated that test accuracy for the unconstrained condition was significantly greater than for the constrained condition ($t(48)=2.50$, $p=0.016$). In sum, findings suggest that our word learning task was challenging for children. Additional exploratory analyses by age group are included in Supplementary Materials.

Why might children have greater test accuracy for the unconstrained condition? Again, visual inspection of the data offered a likely explanation: Children had a novelty preference in the unconstrained condition. A one-sample *t*-test confirmed that children's looks to the novel target were significantly greater than chance in the unconstrained condition before the onset of the target noun (300–2700 ms from sentence onset), indicating that children had a significant novelty bias (one-sample $t(42)=5.93$, $p < 0.001$). Thus, the relatively neutral language in the unconstrained condition may have prompted children to direct attention toward novelty during early moments of sentence comprehension, which in turn supported their word learning. Importantly, we found that the sentences included in the constrained learning condition elicited the opposite pattern of looking behavior: Children generated more looks to the *familiar* object for the constrained condition, as compared to the unconstrained condition, prior to the onset of the target noun (paired-sample $t(42)=2.04$, $p = 0.024$). This finding indicates that the study design was effective in allowing children to generate predictions to the familiar referent, because they generated more looks to the familiar referent in the constrained condition compared to the unconstrained condition.

Finally, for parsimony with prior research (e.g., Borovsky, Elman & Fernald, 2012), we evaluated whether children's PPVT percentiles were correlated with their performance in the learning and test phase of word learning task. We found that children's PPVT percentiles were not significantly correlated with their test accuracy ($r(54)=-0.07$, $p=0.591$). PPVT percentiles were not significantly correlated with the extent to which children generated predictions in the constrained learning context ($r(54)=0.09$, $p=0.517$) or engaged in a predict-and-redirect pattern of looking behavior in the constrained learning context ($r(51)=0.004$, $p=0.977$).

Discussion

A number of recent theories posit that prediction supports language processing (Christiansen & Chater, 2016; Pickering & Garrod, 2013) and learning (Chang, Dell, & Bock, 2006; Dell & Chang, 2014). Although developmental findings are consistent with the view that prediction supports learning, such findings have been largely correlational (e.g., Mani & Huettig, 2012), and it is equally plausible that prediction is solely a *result* of learning, rather than a learning mechanism (Rabagliati, Gambi, & Pickering, 2016). Thus, determining whether and how prediction supports language learning, particularly in children, is crucial to evaluate the central claim of prediction-based learning theories. In the present study, we used an eye-tracking paradigm to evaluate whether particular patterns of children's looking behaviors during learning were correlated with their immediate learning outcomes. Findings revealed that children tended to learn novel words best if they (1) used semantic cues to initially (but erroneously) predict a familiar referent, and (2) redirected attention toward a novel referent in response to the error. Importantly, neither looking behavior before nor after the target noun was independently sufficient to explain differences in learning outcomes. Rather, more successful learners used a predict-and-redirect looking sequence during learning. Thus, the experiment provides an important empirical test of prediction-based theories and suggests that the extent to which children both generate predictions and contend with the arrival of unexpected input influence their ability to encode novel words and their referents.

Why might this particular pattern of looking behavior support learning? The most efficient implementation of this behavioral sequence included two parts: an initial prediction to a familiar referent, and a redirection of attention to a novel referent. The former, shown in previous research to be associated with children's vocabulary size (e.g., Mani & Huettig, 2012), is likely to be beneficial both in strengthening links between words and objects that children have experienced previously, and in readying children to take in subsequent input. The latter behavior – redirecting attention to the novel object once it's named – is likely to signal that children experienced surprisal (e.g., Hale, 2001; Levy, 2008) or prediction error. Upon hearing a novel word, children tended to look to the novel referent, which likely enabled them to more fully encode features of the novel word and its referent. It is possible that processes linked to mutual exclusivity and disambiguation word learning strategies (ME) were at play in this moment of processing (Bion, Borovsky, & Fernald, 2013; Markman & Wachtel, 1988). While many studies of ME focus on children's ability to view or select the appropriate object in response to a novel label (*referent selection*), other work also highlights how this skill connects to successful encoding and subsequent retrieval of that mapping (*referent retention*; e.g. Horst and Samuelson, 2008). ME-associated referent selection mechanisms could have supported children's ability to infer that the novel noun referred to the novel object, as opposed to the familiar object. We would expect these disambiguating mechanisms to operate irrespective of the constraint condition, and therefore support later learning. However, referent selection behavior, as measured by gaze towards the novel noun after it was named, was not independently related to children's test accuracy, suggesting that mutual exclusivity and disambiguation do not fully explain individual differences in learning outcomes. Instead, our results more strongly support an account that reframes referent selection through a lens of (pre-naming) prediction and (post-naming) attentional redirection towards a target object.

Support for the interdependence of initial prediction and attentional redirection was evident in correlational analyses linking behaviors during learning trials with accuracy in test trials. First, in the constrained condition, neither factor alone was significantly related to children's learning outcomes. Second, in the unconstrained condition, the identical sequence of looking behaviors was not related to learning outcomes. In sum, the present findings suggest that the combination of initial predictions and attentional redirection could support children's word learning. Presumably, in the broader context of language learning, this combination operates by strengthening links between familiar and novel words and by allowing children to map novel words to novel referents.

Further, although untested in this experiment, this sequence may have enabled children to link the novel word both to the familiar word *and* to semantically-related words in the sentences. We cautiously speculate that everyday processing of both expected and unexpected words in referential contexts could support the gradual development of children's semantic networks. This word learning account is consistent with Elman's (1990) neural network simulations, which revealed that prediction errors could support encoding of semantic relations between words by exposing learners to their likelihood of appearing in similar contexts. The present findings provide, for the first time, behavioral evidence linking children's prediction errors and immediate learning outcomes that is consistent with prediction-based models of language learning (e.g., Chang et al., 2006; Dell & Chang, 2014;

Elman, 1990). Specifically, our findings indicate that generating an initial prediction *and* changing course in response to a prediction error may be an optimal combination for fostering successful learning in the moments that follow. However, it should be noted that the ideal learner would in fact *not* want to update representations at every turn, because erroneous predictions could arise for other reasons, such as production errors. Instead, the ideal learner is likely to be one who considers both the referential context and their personal history of exposures to words and objects to determine when a prediction error does or does not warrant updating. Understanding this balance is an exciting direction for future work. Research is needed to determine how real-time prediction errors support encoding of new information, and how children's aggregate experiences shape their tendencies to establish meaningful associations between old and new words.

While the present findings suggest that a combination of prediction and attention redirection supports learning, it is unclear what factors drove the observed individual differences in children's looking behavior. Why did some children demonstrate a predict-and-redirect looking pattern, whereas others did not? One possibility is that some children generated stronger initial predictions to familiar referents (e.g., *spoon*) and therefore had more difficulty redirecting attention to novel referents (e.g., *cheem*). That is, the magnitude of children's initial semantic prediction – and by association, the ensuing prediction error – may correlate negatively with their efficiency in redirecting attention. While our analyses revealed that prediction alone was not significantly correlated with learning outcomes, this does not rule out the possibility of hidden variation in prediction magnitude. This possibility is consistent with prior electrophysiological evidence suggesting that prediction errors can indeed vary in magnitude. Specifically, the amplitude of the N400 event-related potential (ERP) corresponds to the degree to which a target noun is expected in a particular context (DeLong, Troyer, & Kutas, 2014; Kutas & Hillyard, 1984; Kutas & Federmeier, 2011). Additionally, the magnitude of prediction errors also varies across individuals in response to the same stimuli (Federmeier, Kutas, & Schul, 2010). Thus, individual differences in children's looking behavior may result from differences in the strength of their initial semantic prediction, with prediction errors of a larger magnitude preventing some children from efficiently redirecting attention in response to the error.

A second possibility is that the locus of individual differences in the predict-and-redirect looking behavior lies in the moment of attention redirection, independent of the initial prediction. While attention to the novel target after it was named was not independently linked to children's novel word learning, we cannot rule out the possibility of covert variation across participants in cognitive control, which has been shown to play a key role in resolving erroneous interpretations during language processing (Hsu & Novick, 2016; Novick, Trueswell & Thompson-Schill, 2005; Woodard, Pozzan & Trueswell, 2016). For example, Woodard and colleagues (2016) found that 4- and 5-year-olds were better able to revise initial misinterpretations of sentences (e.g., *"Put the frog on the napkin onto the box"*) if they performed better on indices of cognitive control. Relatedly, Hsu and Novick (2016) found that adults were better able to revise such misinterpretations in moments following engagement of cognitive control. More broadly, a recent meta-analysis revealed substantial individual differences in children's cognitive control (Doebel & Zelazo, 2015). Thus, in the present study, children's ability to shift attention to a novel referent may have been

contingent, in part, on cognitive control. Variation in this aspect of processing may help explain why some children did not follow the predict-and-redirect looking pattern, which was linked to the most successful learning outcomes. Future studies could evaluate the potential role of cognitive control by including a secondary measure to better understand the interplay of multiple, interrelated factors during language processing and across development.

Our investigation marks an important step to further evaluate whether and how prediction errors support children's word learning. However, there are several limitations of our design that call for future investigations. First, the 5-minute experiment was designed to include six sub-experiments which exposed children to a total of 12 novel words. This was likely a processing burden on our participants, as evident from test accuracy measures. Future studies could decrease the number of novel words or increase the number of exposures in order to increase children's overall test accuracy. Second, in the unconstrained context, which did not include semantic constraints, children had an overall novelty bias during learning. That is, this condition was not truly neutral, and children (predictably) preferred to look toward the novel object, making comparisons between the conditions more challenging. Future studies could address this preference by familiarizing children with pictures of the novel objects prior to the experiment. A third limitation is that our measures of learning only included immediate encoding and short-term recall of novel words, so it is unclear if the learning outcomes observed in the present experiment translate to longer-term retention of novel words. That is, the predict-and-redirect looking sequence could be critical to *or* irrelevant to children's later comprehension or production of novel words. A related limitation is the study's correlational design. It is possible that a latent variable could explain children's performance during learning trials and during test trials, such as cognitive control. Future studies could evaluate related measures of cognition alongside the current measures of prediction and word learning. Finally, in our current design, children received relatively few opportunities to generate prediction errors. In natural processing contexts, children are likely to accumulate many experiences over time in processing old and new words. Future investigations will need to consider how young children form well-calibrated predictions over development, such that they both stay true to their experiential history but also adapt to and learn from the inherent novelty of input.

In sum, the present study makes a number of novel contributions to our understanding of prediction's role in language learning. Most notably, these findings suggest that a full account of prediction-based learning must consider two factors in tandem: (1) the degree to which children generate predictions, and (2) the efficiency with which children act on prediction errors in referential contexts. Our eye-tracking task revealed that neither looking behavior before or after a novel word was independently linked to children's learning outcomes. Instead, these findings suggest that interplay between prediction, prediction errors, and attention redirection may interact to incrementally shape children's growing vocabularies. From here, further research is needed to understand how children's predictions are modified over time with the incremental arrival of more and more new information – a defining feature of children's learning environments.

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

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Appendix

Auditory stimuli for constrained and unconstrained conditions.

	Familiar	Novel
	Constrained	
Going to the park is fun! I picked a pretty _____.	flower	kaki
I like to play in the grass! Next, I'll kick the _____.	ball	gub
Brrr, it's a cold day! Let's put on a _____.	coat	juff
Coloring is the best! I like drawing with a _____.	crayon	toma
Let's go outside! Don't forget to close the _____.	door	pisk
I love the grocery store! Let's buy a(n) _____.	apple	deebo
I love to make music! Can you play the _____?	guitar	blicket
What a windy day! Let's fly a _____.	kite	sprock
Ring ring! Somebody answer the _____.	phone	lort
It's lunch time! Want to eat a _____?	sandwich	manju
Yummy, let's eat soup! I'm going to stir it with a _____.	spoon	cheem
Vroom vroom! You can drive the _____.	truck	fep
	Unconstrained	
You're doing a great job! Check out the _____.	flower	kaki
Hey, look over there! It looks like a _____.	ball	gub
This is so much fun! Look, that's a _____.	coat	juff
I hope you like this game! Which one is the _____?	crayon	toma
Wow! Look at that. That's a _____.	door	pisk
These pictures are fun! That's a(n) _____.	apple	deebo
These pictures rock! Can you see the _____?	guitar	blicket
Well hey there! Do you see a _____?	kite	sprock
Awesome! Take a look at the _____.	phone	lort
Ready for more pictures? Where's the _____?	sandwich	manju
Neat, look over there! Take a look at the _____.	spoon	cheem
Woohoo! I can see a _____.	truck	fep

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Learning	Constrained	Unconstrained
	Yummy! Let's eat soup. I'll stir it with a spoon/cheem.	Neat! Look over there. Take a look at the spoon/cheem.
	Vroom! You can drive the truck/fep.	Woohoo! I can see a truck/fep.
Test		
	Where's the cheem? Where's the fep?	
	Where's the spoon? Where's the truck?	

Figure 1:
Sample block of trials for the constrained condition and the unconstrained condition.

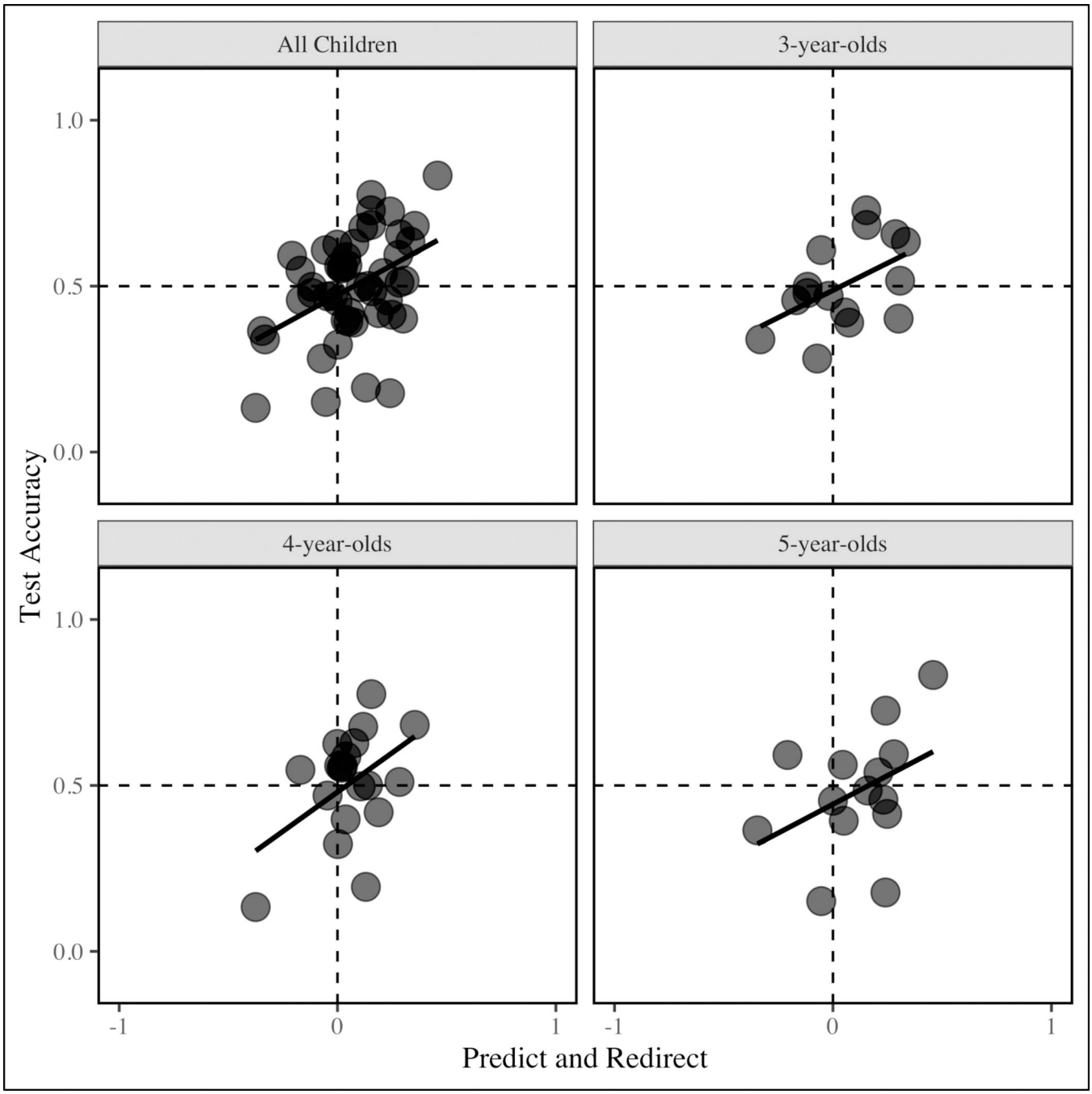

Figure 2:
In the constrained condition, a predict-and-redirect pattern of looking to familiar and novel referents during learning trials was positively correlated with children's accuracy on test trials among the full sample (n=48). Effects varied modestly across three-, four-, and five-year-old children. Points represent individual children and lines represent linear regressions.

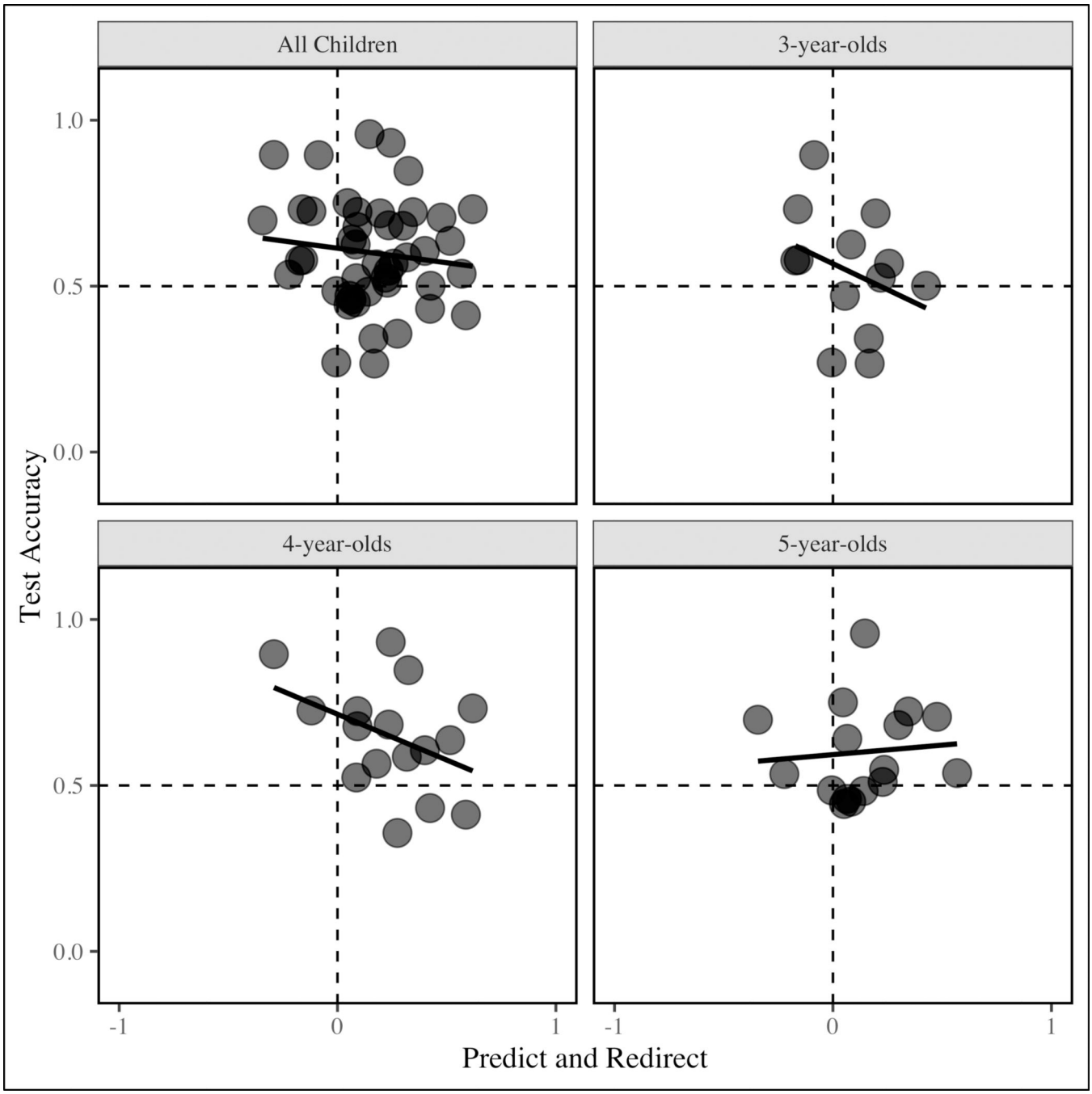

Figure 3:
In the unconstrained condition, a predict-and-redirect pattern of looking to familiar and novel referents during learning trials did not forecast children's accuracy on test trials. Line indicates linear regression and points represent individual subjects.