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Brief article

Individual differences in nonverbal prediction and vocabulary size in infancy

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ABSTRACT

Children who generate and update verbal predictions have larger vocabularies, suggesting that prediction may be a mechanism that supports language learning. We hypothesize that this relation is not confined to the domain of language, but instead signals a broader individual difference in information processing. To investigate this possibility, we tested infants ($n = 50$) in the early stages of vocabulary development (12–24 months) on their ability to generate and update nonverbal, visual predictions. In an eye-tracking task, a central fixation reliably preceded a peripheral target. Then, halfway through the experiment, the peripheral target began appearing on the opposite side. We assessed infants' proficiency in initiating anticipatory eye movements before and after the switch, and found that infants with larger vocabularies did not generate more predictions overall, but were more efficient in updating predictions to the new target side. These findings establish a link between nonverbal prediction and vocabulary in infancy, and suggest a promising means of addressing whether or not prediction abilities are causally related to language learning.

1. Introduction

Human processing of complex information is facilitated by prediction (Bar, 2007; Summerfield & de Lange, 2014). Humans make predictions in many domains, such as vision (Rao & Ballard, 1999; den Ouden, Friston, Daw, McIntosh, & Stephan, 2009; Summerfield & de Lange, 2014), locomotion (Wolpert, Miall, & Kawato, 1998; Wolpert, Ghahramani, & Flanagan, 2001), and language (Rabagliati, Gambi, & Pickering, 2016). In language, prediction enables efficient processing among both adults and children, allowing listeners to keep pace with the rapid information flow of speech (DeLong, Urbach, & Kutas, 2005; Kutas, DeLong, & Smith, 2011; Borovsky, Elman, & Fernald, 2012; Pickering & Garrod, 2013).

In addition to its role in language processing, prediction may also be a mechanism that facilitates language learning. In error-based models of language learning, learners compare predicted input with actual input to gain information about the structure of their language (Chang, Dell, & Bock, 2006; Elman, 1990; Pickering & Garrod, 2013). For example, a child might expect to hear the word 'mouses' but instead hear 'mice,' and update future predictions accordingly (Ramscar, Dye & McCauley, 2013). There are two types of evidence that these models may be valid descriptions of learning. First, it is well-established that children generate predictions during language processing. They are capable of drawing upon many types of linguistic information to anticipate what a speaker is likely to say next, such as phonology (Swingley, Pinto, & Fernald, 1999), semantics (Fernald, Zangl, Portillo, & Marchman, 2008; Fernald, Thorpe, & Marchman, 2010; Mani & Huettig, 2012), morphosyntax (Lew-Williams & Fernald, 2007; Borovsky et al., 2012; Lukyanenko & Fisher, 2016), and speakers' intentions (Kidd, White, & Aslin, 2011). Second, there are individual differences in the extent to which children generate verbal predictions, and these differences are related to children's language proficiency. Compared to children with smaller vocabularies, children with larger vocabularies are more likely to generate predictions in light of new linguistic information (Nation, Marshall & Altman, 2003; Borovsky et al., 2012; Mani & Huettig, 2012). Thus, in line with error-based models of learning, children who generate more verbal predictions and update those predictions efficiently have more advanced language abilities.

This research suggests that children can use multiple sources of information to anticipate downstream words and revise predictions as new linguistic information arrives. Although findings of this nature establish a link between prediction and language learning, they present an interpretational problem. There are a number of plausible explanations: One possibility is that verbal prediction is a capacity that supports vocabulary growth (see Elman, 1990). As reviewed above, prediction

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errors can be used to modify the learner's representations of their language, making future predictions increasingly accurate. In contrast, a second possibility is that verbal prediction is strictly an outcome, rather than a cause, of vocabulary growth (Rabagliati et al., 2016). That is, language users may only begin to generate predictions once they have a fair amount of linguistic knowledge. Evaluating these two possibilities, as well as intermediate views, will aid in understanding the role of prediction in language processing and learning.

To further examine the relation between prediction and language learning, we used two new approaches. First, we focused on infants between 1 and 2 years of age. Previous studies showing links between prediction and vocabulary have tested children between 2 and 7 years who already comprehend and produce multiword sentences. If prediction plays a role in supporting the initial stages of language learning, then infants' prediction abilities should already be linked to their budding linguistic knowledge. Second, in the current study we evaluated whether prediction as a domain-general capacity may be related to language learning. That is, we did not aim to replicate previously established relations between verbal prediction and vocabulary. Instead, based on views of prediction as a general capacity that is present in multiple domains and possibly interacts across domains (Bar, 2007; Lupyan & Clark, 2015), we examined relations between nonverbal (i.e., visual) prediction and vocabulary size. We reasoned that differences in nonverbal prediction, as compared to verbal prediction, are less likely to be the direct result of vocabulary differences. This cross-domain approach represents a new direction for understanding the relation between prediction abilities and language proficiency.

Our investigation of how infants make and update nonverbal predictions included two main hypotheses. First, we hypothesized that the *quantity* of predictions that infants generate in a nonverbal task would be linked to vocabulary. Among older children, those with larger vocabularies, as compared to those with smaller vocabularies, are more likely to make verbal predictions (Nation, Marshall, & Altmann, 2003; Borovsky et al., 2012; Mani & Huettig, 2012). We expected that this relation would hold earlier in development and apply to the domain of nonverbal prediction. Second, we hypothesized that the *quality* of infants' nonverbal predictions would be linked to vocabulary. In error-based models, learners update predictions when they encounter incongruent information (Chang et al., 2006). Assuming these models are relevant for explaining learning toward the beginning of life, we expected that infants with larger vocabularies would be more successful in updating nonverbal predictions after observing unexpected information.

To evaluate these hypotheses, we tested 12- to 24-month-old infants in a visual prediction task, using anticipatory eye movements (AEMs) as a measure of prediction. In a second eye-tracking task, we controlled for differences in infants' speed of visual processing. We compared performance on these tasks to infants' vocabulary size (MCDI). Together, we used these measures to evaluate whether and how nonverbal prediction abilities relate to infants' early language development.

2. Method

2.1. Participants

Participants were 50 infants (26 female) from monolingual English-speaking families who ranged in age from 12 to 24 months ($M = 18$, $SD = 3.5$). Infants were full-term and had no known vision or hearing impairments. We excluded an additional 14 infants from all analyses due to parental report of developmental delay (1), bilingual language exposure (2), fussiness such that less than 50% of trials were code-able (8),[1] or computer error (3). We excluded 6 of the 50 infants from visual processing task analyses due to computer error (4) or experimenter error (2). The Princeton University Institutional Review Board approved all research protocols, and a legal guardian provided informed consent for each infant.

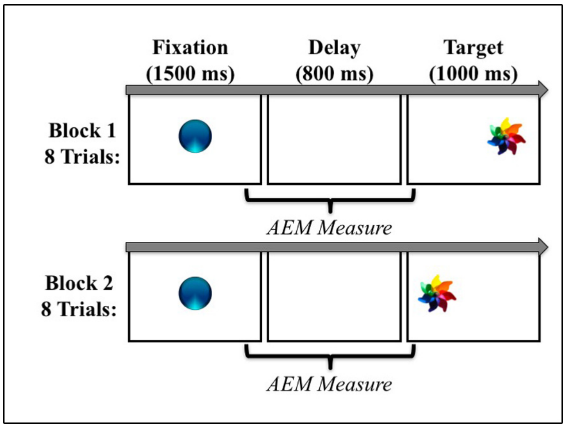

Fig. 1. Schematic of the prediction task. Infants saw two blocks of trials. In Block 1, the target always appeared on one side (e.g., right). In Block 2, the target always appeared on the opposite side (e.g., left). On each trial, we measured infants' anticipatory eye movements (AEMs), defined as looks to either target location during a time window from 200 ms before center fixation offset until 200 ms after target onset (AEM Measure).

2.2. Stimuli – Prediction task

On each trial, infants saw a central, looming fixation paired with a slide-whistle sound for 1500 ms. After an 800-ms delay, infants saw a peripheral, spinning target paired with another slide-whistle sound for 1000 ms (Fig. 1). Importantly, infants saw two blocks of trials. In the first block (trials 1–8), the target always appeared on one side, and in the second block (trials 9–16) its location switched sides. Block 1 target location was counterbalanced across infants.

On each trial, we measured infants' anticipatory eye movements (AEMs). As shown in Fig. 1, we conservatively defined AEMs as looks to either peripheral location during a time window from 200 ms before center fixation offset until 200 ms after target onset. This temporal window accounts for time needed to generate a saccade (Canfield, Smith, Brezsnyak, & Snow, 1997; Hallett, 1986; Matin, Shao, & Boff, 1993). AEMs were included in analyses regardless of infants' initial looking location.

Infants also saw a filler trial every 4 trials to maintain their attention. Fillers consisted of 5-s movies of a kaleidoscope paired with soft chimes. There was a 500-ms blank inter-trial interval.

2.3. Stimuli – Visual processing task

On each trial, infants saw a central fixation for 1000 ms, followed by a peripheral target for 1000 or 1250 ms (Fig. 2). Infants saw two types of trials. On gap trials, there was a 250-ms temporal gap between fixation offset and target onset. On overlap trials, there was a 250-ms temporal overlap between the fixation and the target. Unlike the prediction task, the target location did not follow a consistent pattern. Thus, infants were unable to accurately predict the target location. Trials appeared in one of two quasi-randomized orders, such that neither trial type (gap or overlap) nor target side (right or left) repeated for more than 3 trials sequentially. Fixation and target were stationary, and there were no auditory stimuli.

On each trial, we measured infants' reaction time (RT), defined as the time of the first target look occurring 200 ms or later after target onset (Fig. 2, "RT measure"). On overlap trials, the central stimulus

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[1] We compared age and vocabulary measures for excluded and included infants, and found no differences in age [$t(8.58) = 0.06$, $p = 0.95$], MCDI comprehensive vocabulary size [$t(11.26) = -0.63$, $p = 0.54$], or MCDI productive vocabulary size [$t(11.71) = -0.40$, $p = 0.695$].