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RESEARCH ARTICLE

Infants' lexical comprehension and lexical anticipation abilities are closely linked in early language development

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Abstract

Theories across cognitive domains propose that anticipating upcoming sensory input supports information processing. In line with this view, prior findings indicate that adults and children anticipate upcoming words during real-time language processing, via such processes as prediction and priming. However, it is unclear if anticipatory processes are strictly an outcome of prior language development or are more entwined with language learning and development. We operationalized this theoretical question as whether developmental emergence of comprehension of lexical items occurs before or concurrently with the anticipation of these lexical items. To this end, we tested infants of ages 12, 15, 18, and 24 months ($N = 67$) on their abilities to comprehend and anticipate familiar nouns. In an eye-tracking task, infants viewed pairs of images and heard sentences with either informative words (e.g., *eat*) that allowed them to anticipate an upcoming noun (e.g., *cookie*), or uninformative words (e.g., *see*). Findings indicated that infants' comprehension and anticipation abilities are closely linked over developmental time and within individuals. Importantly, we do not find evidence for lexical comprehension in the absence of lexical anticipation. Thus, anticipatory processes are present early in infants' second year, suggesting they are a part of language development rather than solely an outcome of it.

1 | INTRODUCTION

A number of theories propose that anticipating upcoming information supports processing in various domains (Bar, 2007; Clark, 2013; Friston & Kiebel, 2009), including vision (den Ouden et al., 2009; Rao & Ballard, 1999; Summerfield & de Lange, 2014), locomotion (Wolpert et al., 2001), and language (Kutas et al., 2011; Pickering & Gambi, 2018; Pickering & Garrod, 2013). For example, psycholinguistic theories have emphasized the role of anticipatory processes (such as prediction and priming) in enabling rapid, accurate processing of incoming speech (Christiansen & Chater, 2016) and in coordinating dialogue (Pickering & Garrod, 2013). Supporting these views, numerous findings indicate that adult listeners can anticipate upcoming words during real-time language processing (for reviews see: Federmeier, 2009; Kutas, et al., 2011; Pickering & Gambi, 2018). Anticipating upcoming information ostensibly allows us to resolve ambiguous perceptual input (Sohoglu & Davis, 2016; Trecca et al., 2019; Yurovsky et al., 2017), to segment smaller units of information from a continuous stream (Elman, 1990; Zacks et al., 2011), to transform smaller units of information into larger ones for further processing (Christiansen & Chater, 2016), and to encode new information more effectively (Gambi et al., 2021; Reuter et al., 2019).

Beyond its proposed role in enabling efficient processing, anticipatory mechanisms have also been proposed to support the development of complex perceptual-cognitive abilities, including language (Dell & Chang, 2014; Elman, 1990; Joanisse & McClelland, 2015; McClelland, 2002; Rescorla & Wagner, 1972). Anticipating upcoming information during real-time language processing ostensibly allows learners to incrementally learn over the course of many day-to-day processing experiences. For instance, by accurately anticipating upcoming, familiar words, learners may increase the efficiency of their language comprehension which in turn allows them to better contend with novel information as it arises (Fernald et al., 2006; Gambi et al., 2021; Marchman & Fernald, 2008). Errors could also be informative for learners (Chang et al., 2006; Dell & Chang, 2014; Elman, 1990). For example, an English learner might reasonably expect ‘mouses’ as the plural form of ‘mouse,’ and computational evidence suggests that these kinds of mistakes could incrementally help guide them to the correct, novel word (Ramscar et al., 2013). In sum, some developmental theories (e.g., Dell & Chang, 2014) propose that anticipating upcoming information during real-time language processing incrementally shapes learners' comprehension efficiency and vocabularies over the course of many everyday language experiences.

While beyond the scope of the current study, it is important to consider the range of possible mechanisms that could underlie infants' observed behaviors during real-time language processing. In eye-tracking paradigms, looks to a visual referent are generally taken as evidence for the activation of relevant semantic representations (Cooper, 1974; Fernald et al., 2008; Tanenhaus et al., 1995), and anticipatory eye movements have similarly been taken as evidence for the pre-activation of lexical representations (Altmann & Kamide, 1999; for review see Kamide, 2008). However, it is important to recognize the limitations of these eye tracking methods and the broad range of potential interpretations which arise from using behavioral measures. Namely, do infants' anticipatory eye movements reflect top-down predictive mechanisms, bottom-up priming mechanisms, or other processes entirely? We have used the term ‘anticipation’ to refer to the ability to shift attention to a referent prior to its explicit naming, with the goal of being agnostic about the specific cognitive mechanisms involved. While the listener may engage predictive processes per se, where top-down processes result in the pre-activation of lexical representations (e.g., Elman, 1990), they could also have relied on priming processes (i.e., semantic associations between related words). That is, informative words like *eat*, *yum*, and *mouth* may primed a listener to look at edible objects generally or at the cookie specifically (see Arias-Trejo & Plunkett, 2009), or allowed for greater integration of these words (as would be the case for measures collected after target word onset, Kutas et al., 2011). Anticipatory looking—shifting attention to a visual referent before it is named—is consistent with both prediction or associative priming accounts, and this experiment was not designed to distinguish between these two closely-related constructs. Indeed, to our knowledge, few psycholinguistic investigations have directly aimed to differentiate these mechanisms (Lau et al., 2013; Otten & Van Berkum, 2008). Needless to say that a complete discussion of prediction versus priming mechanisms is beyond the scope of this paper as well as determining whether it is prediction or priming that is underlying the anticipatory looks during standard sentence comprehension paradigms as this is a broad limitation in this literature in both developmental and non-developmental populations.

In addition to explanations based on prediction or priming, it is possible that infants' looking behaviors in the present study might reflect *neither* of these anticipatory mechanisms. Looking to a target image does not conclusively indicate that the target lexical representation is (pre)activated. Infants might comprehend semantically-related words and activate related lexical representations (e.g., eat, yum, mouth, food) without ever activating the lexical representation for the specific target word (e.g., cookie). The "spreading activation" of representations (Collins & Loftus, 1975) could stop short of the target word itself. A related possibility is that the target lexical representation is only activated indirectly, via a cascade of auditory and visual processes. Under this account, the auditory stimuli activate a network of semantically-related words, which causes infants to look to the target image. Then, as a result of this looking behavior, the visual stimuli (e.g., an image of a cookie) causes infants to activate the corresponding lexical representation for the target word. Eye-tracking paradigms inherently allow for both auditory and visual routes to lexical activation, and there are multiple ways in which listeners could potentially access the meanings of words in these kinds of tasks (Huettig et al., 2011).

The debate with regards to which mechanisms might be supporting anticipatory looking should also be considered in relation to a related literature on error processing during language comprehension in young infants. Predictive processing has two major mechansims or signatures. One is anticipation or prediction of upcoming stimuli. The second is error processing where error signals emerge after an incorrect prediction. As reviewed recently in Babineau et al. (under review), there is strong evidence for error processing in language comprehension in young children and increasing evidence for similar types of error processing in infants younger than 24 months. As argued in Babineau, Havron, Dautriche, de Carvalho & Christophe, under review, (under review), these findings provide evidence that young infants may be engaging in predictive processing and complement studies showing anticipation of upcoming words. Error processing and anticipation are both part of predictive processing and thus these related literatures might together point to the plausibility of predictive processes rather than priming or spreading activation, as supporting language comprehension in infants.

Returning to the discussion of how anticipatory processes fit into language development, a growing number of findings suggest that infants and children can anticipate upcoming information during real-time language processing using a variety of linguistic cues (Borovsky et al., 2012; Fernald et al., 2008; Gambi et al., 2021; Havron et al., 2018; Kedar et al., 2017; Kidd et al., 2011; Lew-Williams & Fernald, 2007; Lukyanenko & Fisher, 2016; Mani & Huettig, 2012; Mornati et al., 2022; Reuter et al., 2019; Reuter et al., in press; Ylinen et al., 2016; Yurovsky et al., 2017). Although some investigations have analyzed behaviors after the onset of a target word (e.g., Arias-Trejo & Plunkett, 2009), anticipatory eye movements have become an established behavioral marker for prediction and priming mechanisms, beginning with adult eye-tracking studies (Altmann & Kamide, 1999; for review see Kamide, 2008) and extending to developmental investigations (Borovsky et al., 2012; Kidd et al., 2011; Mani & Huettig, 2012). For example, Mani and Huettig (2012) found that 2-year-old children used informative verbs (e.g., The boy eats the big cake) to look to the upcoming target referent (e.g., a cake) before it was named. In a more recent example, Mornati et al. (2022) found that infants in the second postnatal year use gender to look towards an upcoming target referent. Similarly, listeners' eye movements after the target referent is named are broadly thought to reflect the speed and accuracy of their comprehension (Fernald et al., 2006, 2008; Marchman & Fernald, 2008). Thus, a body of prior research has identified behavioral markers of anticipation and comprehension, and a growing number of findings indicate that infants and children can comprehend and anticipate familiar words during moment-to-moment language processing.

However, the extent to which anticipating upcoming information supports language development is the subject of ongoing debate for a number of reasons (Babineau et al., under review; Christiansen & Chater, 2016; Huettig, 2015; Huettig & Mani, 2016; Rabagliati et al., 2016). A primary reason for skepticism is that existing empirical evidence is often ambiguous. One source of ambiguity is that behavioral measures such as anticipatory eye movements often show compelling evidence for anticipatory processing beginning in early childhood, but these measures do not conclusively distinguish between specific anticipatory mechanisms such as prediction and priming. The current study draws primarily from research on prediction, but the goal is **not** to disentangle prediction or priming processes early in development. Instead, we aim to understand if anticipatory processes, defined more generally as the use of current input to efficiently identify upcoming words and referents, are a part of infants' growing knowledge of words or if they only emerge following a period of robust knowledge of words.

A second and related source of ambiguity is that most developmental studies evaluating anticipatory processes in language processing have focused on later stages of development (i.e., 2 years of age and older). Previous investigations have observed positive relations between anticipatory abilities and vocabulary size (Borovsky et al., 2012; Lew-Williams & Fernald, 2007; Mani & Huettig, 2012; Ylinen et al., 2016), and recent work found a positive relation between anticipatory processes and vocabulary change longitudinally (Gambi et al., 2021). But, existing work has failed to systematically evaluate when and how anticipatory abilities might emerge over the course of development. It is unclear how mechanisms like prediction or priming might co-develop alongside learners' increasing comprehension abilities and word knowledge. Thus, lexical anticipation could be strictly an outcome of prior development and a marker of 'expertise,' rather than a mechanism that shapes learners' emerging language abilities (Christiansen & Chater, 2016; Rabagliati et al., 2016). This leaves open a question that is central to theories of prediction: Are lexical comprehension and lexical anticipation abilities inherently intertwined, such that they emerge concurrently during early language development, or do comprehension and anticipation abilities emerge sequentially, with the former shaping the latter but not vice-versa?

One important way to answer these questions is to investigate anticipation and comprehension in early stages of language development. The time period from 12 to 24 months is a period of development with well-documented, dramatic increases in comprehension abilities and vocabulary size (Fernald et al., 2006, 2008; Marchman & Fernald, 2008). Thus, investigating these questions in infants in the second postnatal year (12–24 months) is crucial to answering the question of whether anticipatory processes are supporting language development or vice versa (see also Babineau et al., under review for a similar argument).

To date, the evidence of anticipatory language processing in infants is limited and studies that link anticipation and comprehension are particularly needed to address this gap. While the majority of research has established anticipatory processing in populations older than this period, there have some studies of anticipatory processing in young infants. For example, Mornati et al., (2022) report evidence of anticipation of upcoming target nouns in infants younger than 24 months. Moveover, there are numerous studies that have found evidence of non-linguistic prediction in infants aged 12 months and younger (e.g., Reuter et al., 2018; Zhang et al., 2018). Babineau et al. (under review) highlight studies showing evidence of error processing in language comprehension in this period of infancy but limited evidence of anticipatory looking per se. While there is increasing information as to the anticipatory abilities of infants from 12 to 24 months, the current evidence is still highly limited. Moreover, studies that link anticipation with comprehension abilities can be particularly informative as they can answer the question whether there is sequential development of comprehension and then anticipation or whether they represent more entangled processes.

To continue to address this limitation in the field, we conducted an eye-tracking study that evaluated 12- to 24-month-old infants' abilities to comprehend familiar nouns and to anticipate their arrival based on informative, semantically-related words. Infants viewed two images (e.g., a cookie and a shoe) and heard corresponding sentences: Half included informative words and phrases which could allow infants to anticipate an upcoming target noun (e.g., *Let's go eat. Oh, yum yum! Open your mouth! Where's the cookie? Find the cookie!*) and half were neutral (e.g., *Look at that! There it is! Do you see it? Where's the cookie? Find the cookie!*).[1] Specifically, we tested 12-, 15-, 18-, and 24-month-old infants in a cross-sectional study. By examining the developmental trajectory of infants' abilities to comprehend and anticipate familiar words during real-time language processing, this study takes an important step toward clarifying the role of anticipatory mechanisms like prediction and priming in early language development. If robust comprehension emerges *before* infants can anticipate upcoming words (Christiansen & Chater, 2016; Rabagliati et al., 2016), then one should expect to observe a sequential developmental pattern (i.e., a prolonged period of reliable comprehension without any anticipatory behaviors). Alternatively, if anticipatory mechanisms support developmental increases in comprehension, and vice versa (e.g., Dell & Chang, 2014), then one should expect comprehension and anticipation abilities to emerge concurrently over the course of the second postnatal year.

2 | METHOD

2.1 | Participants

Participants were 67 infants (37 male) from monolingual English-speaking households. Infants ranged from 11 to 25 months of age ($M = 18$ months, $SD = 4.4$ months). Infants were born full-term (37 weeks or greater) and had no known hearing or vision impairments. We tested and excluded an additional 37 infants (36% of 104 total) due to: fussiness such that the infant completed less than 50% of trials (23), inattention or head movement during eye-tracking such that less than 20% of total possible samples were tracked during the entire experiment (12), parental report of diagnosed developmental delay (1), and experimenter error (1). The [blinded] Institutional Review Board approved this research protocol (IRB record number 7211), and a legal guardian provided informed consent for each infant.

In order to further evaluate developmental changes in our measures of interest, we divided infants into four age groups for some analyses: 12 months ($n = 16$, range = 12–13.5 months, $M = 12.6$ months,

[1]This design is comparable to prior developmental investigations of anticipatory language processes in children (e.g., Mani & Huettig, 2012) but we included multiple informative words (e.g., *eat, yum, mouth*) prior to onset of the target noun (e.g., *cookie*) in order to accommodate infants' emerging language proficiency.

SD = 0.5 months), 15 months (*n* = 16, range = 15.1–16.4 months, *M* = 15.8 months, *SD* = 0.4 months), 18 months (*n* = 18, range = 18–19.6 months, *M* = 18.7 months, *SD* = 0.4 months), and 24 months (*n* = 17, range = 23.6–25.3 months, *M* = 24.6 months, *SD* = 0.5 months). We determined the sample size for the present study based on prior studies evaluating infants' lexical anticipation and comprehension abilities (e.g., Bergelson & Aslin, 2017a; Kedar et al., 2006; Kedar et al., 2017; Kidd et al., 2011).

The present study was conducted according to guidelines laid down in the Declaration of Helsinki, with written informed consent obtained from a parent or guardian for each child before any assessment or data collection. All procedures involving human subjects in this study were approved by the Institutional Review Board at Princeton University.

2.2 | Stimuli

Auditory stimuli consisted of two types of pre-recorded sentences. Anticipatory sentences contained informative, semantically-related words that infants could use to anticipate an upcoming target noun (e.g., *Let's go eat. Oh, yum yum! Open your mouth! Where's the cookie? Find the cookie!*). We selected informative words based on semantic relatedness and based on comprehension estimates from Wordbank (Frank et al., 2016). Neutral sentences, in contrast, did not include any words that could be used to anticipate the target noun (e.g., *Look at that! There it is! Do you see it? Where's the cookie? Find the cookie!*). See the Supplementary Material for all stimuli.

A female, native speaker of English recorded auditory stimuli with infant-directed intonation. Recordings took place in a sound-attenuated room and utilized Audacity software (Version 2.2.1, Audacity Team, 2017). We used Praat (Boersma & Weenink, 2017) to process recordings. First, we normalized phrase durations across conditions (e.g., such that *Let's go eat* was the same duration as *Look at that!*), and inserted a 500-ms pause between phrases. Next, we spliced recordings to ensure that the final two phrases for each noun (e.g., *Where's the cookie? Find the cookie?*) were identical across conditions. Finally, we normalized the total duration of each stimulus to the overall mean duration. In sum, each auditory stimulus had a total duration of 8379 ms, with the onset of the first informative word (e.g., *eat*) occurring at 875 ms, the onset of the target noun (e.g., *cookie*) occurring at 5971 ms, and an average intensity of 60 dB.

Visual stimuli were images of the four target nouns: *ball, cookie, cup,* and *shoe*. There were two exemplar images for each target noun (e.g., a blue ball and a red ball). The target image was approximately 450 × 450 pixels and appeared on a 500 × 500 pixel white background. Visual stimuli appeared in yoked pairs (i.e., *ball-cup*, and *cookie-shoe*). Exemplars also appeared in yoked pairs (e.g., a blue ball always appeared with a green cup) and each yoked pair appeared twice during the experiment (once with a neutral sentence and once with an anticipatory sentence).

During each trial, visual stimuli appeared 500 ms prior to the onset of auditory stimuli and remained visible for 8500 ms after the onset of auditory stimuli, such that the duration of each trial was 9000 ms total. Trials appeared in one of two quasi-randomized orders (between subjects). Orders counterbalanced target side (right/left), ensuring that target side and condition (anticipatory/neutral) did not repeat for more than three trials sequentially. Filler trials occurred as the first trial and every four trials thereafter. Filler trials consisted of a 1280 × 1024 pixel image (e.g., snowflakes) and positive statements (e.g., *Yay! Look! Do you see this pretty picture? Let's see some more!*). In sum, the experiment included 8 anticipatory trials, 8 neutral trials, and 5 filler trials. Each item-pair was presented 8 times in total (i.e., item 1: anticipatory/neutral; item 2: anticipatory/neutral) with the item-pair presented twice in each group of 4 non-filler trials with the item positions counterbalanced across trials. All stimuli and experimental are available in SupplementaryMaterials.

2.3 | Vocabulary measure (MCDI)

We used short-form versions of the MacArthur-Bates Communicative Development Inventory (MCDI; Fenson et al., 2000) to evaluate infants' vocabulary size and to assess their reported comprehension and production of specific words. We modified each short-form to include all target nouns (i.e., *ball, cookie, cup, shoe*) and all the informative words included in anticipatory sentences (i.e., *play, toy, throw, eat, yum, mouth, drink, water, juice, walk, foot,* and *sock*). Thus, the modified MCDI allowed us to assess infants' overall vocabulary size, as well as their comprehension and production of all target nouns and informative words.

2.4 | Procedure

The study took place in a sound-attenuated room at the [blinded]. Infants sat on their caregiver's lap, approximately 60 cm from the eye-tracker. The experimenter sat opposite from the infant and controlled the study from a Mac host computer, using EyeLink Experiment Builder software (SR Research, Mississauga, Ontario, Canada). Before beginning the task, the experimenter placed a target sticker on the infant's face to allow the eye-tracker to record their eye movements and calibrated the eye-tracker for the infant, using a standard 5-point procedure. The experimenter placed a visor over the caregiver's eyes after calibration to prevent caregivers from influencing their infant's behavior during the task. Infants viewed stimuli on a 17-inch LCD monitor and an EyeLink 1000 Plus eye-tracker, sampling at 500 Hz, recorded their eye movements. The average duration of the eye-tracking task was approximately 4 min. Caregivers completed the MCDI immediately after the eye-tracking task.

3 | RESULTS

3.1 | Vocabulary analyses (MCDI)

To confirm the expected increases in infants' vocabulary size during this developmental period (Fernald et al., 2006), we analyzed the number of MCDI short-form words that infants were reported to comprehend and produce. Four infants did not contribute MCDI data, due to experimenter error. As expected, linear models indicated that the number of words infants reportedly comprehended increased with age ($\beta = 2.93$, $t = 3.73$, $p < 0.001$) as did the number of words they reportedly produced ($\beta = 5.67$, $t = 10.30$, $p < 0.001$). Additional descriptive statistics and exploratory analyses for MCDI data are available in SupplementaryMaterials.

3.2 | Eye-tracking analyses

During the eye-tracking task, we recorded infants' looks to the visual stimuli, and coded looks to the target and distractor as any look within the 500 × 500 pixel area surrounding the target or distractor images (250,000 of 1,310,720 pixels, 19% of the 1280 × 1024 screen). We used R software (version 3.6.0) for analyses. We excluded track-loss samples prior to aggregating data, ultimately including a total of 3,067,352 out of the original 5,600,904 samples in analyses (55%). This rate of exclusion may be higher than related studies for multiple reasons: (1) our ROIs are more conservatively determined (i.e., smaller proportion of the screen) and (2) we used an SR Eyelink which has high precision for a system used with infants but can also result in some more points dropped when the system is not

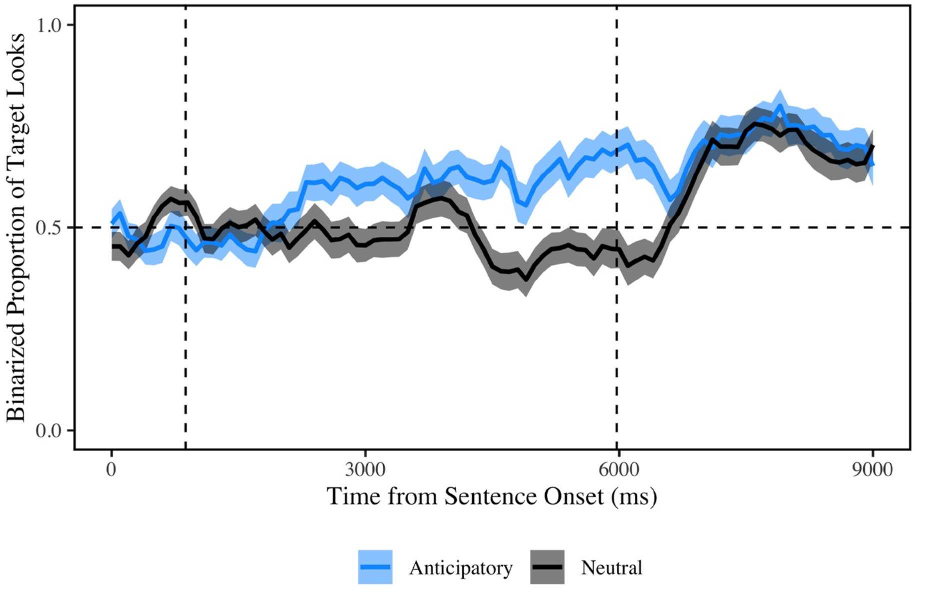

FIGURE 1 Binarized proportion of looks to the target image (e.g., cookie) during anticipatory sentences (blue) and neutral sentences (grey) for all infants 12–24 months old (n = 67). Auditory stimulus onset is at 0 ms. Line shading represents one standard error from the mean for each condition, averaged by subjects. Horizontal dashed line indicates chance performance. Vertical dashed lines indicate the onset of the first informative word for anticipatory trials (e.g., eat) and the onset of the target noun (e.g., cookie).

able to gather sufficient information (e.g., during a blink, if movement is beyond the tolerance of the system).

We then averaged infants' proportion of looks to the target image within 100-ms bins (Figure 1). We choose to create 100 ms bins despite the high resolution of the eye tracker to balance a number of factors: (1) the likely slowness of the underlying cognitive signal (infants engaging in sentence processing and saccading to different targets on the screen which occurs much more slowly than the sampling of the eye tracker); (2) wanting to be robust to the individual time-samples that may be dropped within bins; (3) not wanting to have too many samples with regards to correcting for multiple comparisons with (4) the need to have sufficient resolution to disentangle the responses to the anticipatory window from the comprehension window. In particular, our research question requires us to disentangle the two time periods of anticipation and comprehension and 100-ms bins are more than sufficient for this purpose. Future exploratory research could potentially use the increased temporal precision of the eye tracker to look at other research questions.

Within each 100-ms bin, due to the saccadic nature of eye movements, infants typically fixated only one image (40,908 of 43,446 bins, 94%). Therefore, as in prior studies (Huang & Arnold, 2016; Reuter et al., 2018), we binarized infants' proportion of target looks within each bin: Looks were coded either as 1 or 0 if the proportion was greater than or less than 0.50, respectively, and proportions equal to 0.50 were excluded (35 of 43,446 bins, 0.08%).

We analyzed infants' binarized proportion of target looks with a generalized linear mixed-effects model, using the lme4 package (version 1.1-21, Bates et al., 2015) and the lmerTest package (version 3.1–0, Kuznetsova et al., 2017). The model included fixed effects for age (continuous), condition (anticipatory/neutral) and time (100-ms bins, 0–9000 ms from trial onset), and their interactions. The model also included the maximal random effects structure for subjects and items (Barr et al., 2013). Results revealed effects for age (β = 0.134, z = 3.11, p = 0.002), condition (β = 0.304, z = 2.11,

$p = 0.034$), and time ($\beta = 0.350$, $z = 6.76$, $p < 0.001$). Respectively, these findings indicated three expected effects: Target looks increased with age, infants generated more target looks for anticipatory trials than for neutral trials, and target looks increased over time as the sentences unfolded. Importantly, results revealed a three-way interaction of age, condition, and time ($\beta = 0.111$, $z = 1.99$, $p = 0.046$), indicating that looking behavior varied as a function of all three factors.

We next conducted more fine-grained analyses to address our main question: Do infants' comprehension and anticipation abilities emerge concurrently or sequentially? To assess infants' emerging *comprehension* abilities, we divided infants into four age groups (12, 15, 18, and 24 months) and evaluated their looking behavior with cluster-based permutation analyses (for details on this approach, see Maris & Oostenveld, 2007). Specifically, we calculated infants' binarized proportion of target looks (averaged across trial types) within 100-ms time bins (0–9000 ms from trial onset). We conducted a binomial test to compare target looks to chance (0.50) within each time bin after the onset of the target noun (6000–9000 ms from trial onset), identified clusters of time bins, and summed binomial test estimates within each cluster. Next, we randomly permuted each infant's binarized proportion of target looks 1000 times (i.e., randomly re-coding target looks as distractor looks and vice-versa for each trial) for all of their time bins, thereby creating the null distribution for comparison. We then repeated the cluster-finding procedure and summation of test estimates with these permuted data. Finally, we calculated p-values: The p-value for each observed cluster was calculated as the proportion of permuted cluster test estimates that were greater than the observed cluster test estimates.

If infants reliably comprehended target nouns (e.g., *cookie*), then we expected their proportion of target looks to be significantly greater than chance after the onset of the target noun, indicating that they oriented to the appropriate referent once it was named. Analyses revealed no significant clusters for 12-month-olds (ps > 0.05), two significant clusters for 15-month-olds (7100–8500 ms, $p < 0.001$; 8700–9000 ms, $p = 0.049$), a significant cluster for 18-month-olds (6700–9000 ms, $p < 0.001$), and a significant cluster for 24-month-olds (6300–9000 ms, $p < 0.001$). Thus, results from our eye-tracking paradigm indicate that infants' comprehension of familiar nous was apparent beginning at 15 months.

Next, to assess infants' emerging *anticipation* abilities, we again used cluster-based permutation analyses. We calculated infants' binarized proportion of target looks during anticipatory trials within 100-ms time bins (0–6000 ms from trial onset). If infants use informative words (e.g., *eat*) to anticipate upcoming nouns (e.g., *cookie*) then their proportion of target looks should be greater than chance after the onset of the first informative word and prior to the onset of the target noun (1100–6000 ms from trial onset), indicating that they generated anticipatory eye movements towards the appropriate visual referent before it was named. Analyses revealed no significant clusters for 12-month-olds (ps > 0.05), two significant clusters for 15-month-olds (2300–3100 ms, $p < 0.001$; 4100–4500 ms, $p = 0.038$; 5000–5500 ms, $p = 0.005$), two significant clusters for 18-month-olds (3200–4100 ms, $p = 0.001$; 4600–6000 ms, $p < 0.001$), and a significant cluster for 24-month-olds (3700–6000 ms, $p < 0.001$). This reveals that infants' anticipation abilities—like their comprehension abilities—were apparent beginning at 15 months (Figure 2).

Lastly, we found that anticipation and comprehension related to one another at the individual subject level across age groups (see SupplementaryMaterials for details). In brief, regression results indicated that infants' anticipation abilities were positively related to their comprehension abilities ($\beta = 0.31$, $t = 5.96$, $p < 0.001$). We also found that infants' anticipation measures were positively related to vocabulary size ($\beta = 0.34$, $t = 2.81$, $p = 0.007$), as observed in prior investigations (e.g., Mani & Huettig, 2012).

Together, our findings indicated that infants' abilities to comprehend and anticipate familiar words changed over the second postnatal year. Importantly, developmental increases in comprehension closely mirrored increases in anticipation: As soon as infants reliably comprehended target nouns

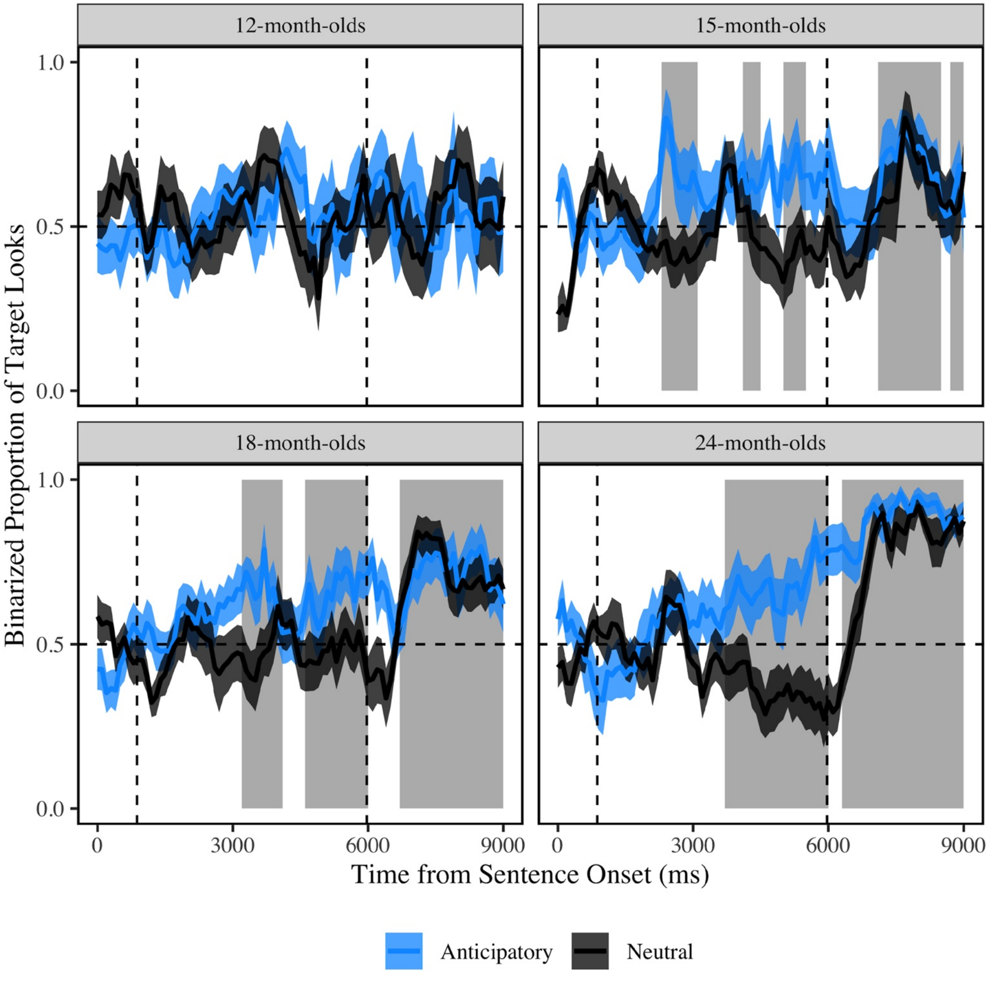

FIGURE 2 Binarized proportion of looks to the target image (e.g., cookie) during anticipatory sentences (blue) and neutral sentences (grey) for 12-month-olds ($n = 16$), 15-month-olds ($n = 16$), 18-month-olds ($n = 18$) and 24-month-olds ($n = 17$). As in Figure 1, auditory stimulus onset is at 0 ms. Line shading represents one standard error from the mean for each condition (averaged by subjects). Horizontal dashed line indicates chance performance. Vertical dashed lines indicate the onset of the first informative word for anticipatory trials (e.g., eat) and the onset of the target noun (e.g., cookie). Area shading indicates significant results (ps < 0.05) from two cluster-based permutation analyses (Maris & Oostenveld, 2007): If infants comprehend target nouns, then we expect target looks (averaged across both trial types) to be greater than chance after the onset of the target noun (6000–9000 ms). If infants anticipate target nouns, then we expect target looks to be greater than chance for anticipatory trials after the onset of the first informative word and before the onset of the target noun (1100–6000 ms). Results reveal the concurrent emergence of infants' comprehension and anticipation abilities.

(e.g., *cookie*), they were able to use semantically-related words (e.g., *eat*) to accurately anticipate their arrival during real-time language processing. This study provides behavioral evidence that comprehension and anticipation emerge concurrently during infancy, suggesting that anticipatory mechanisms may shape the course of early language development.

4 | DISCUSSION

There is converging support that the ability to anticipate the arrival of upcoming words enables efficient language comprehension in adults (Christiansen & Chater, 2016; Kutas et al., 2011; Pickering & Gambi, 2018; Pickering & Garrod, 2013), and it has been documented that young children can use current input to more rapidly recognize upcoming words in speech (Borovsky et al., 2012; Fernald et al., 2008; Gambi et al., 2021; Lew-Williams & Fernald, 2007; Lukyanenko & Fisher, 2016; Mani & Huettig, 2012; Reuter et al., 2019; Reuter et al., in press). However, the role of these anticipatory processes in language development remains uncertain. Some models suggest that anticipation (particularly prediction) enables increases in comprehension and vice-versa (e.g., Dell & Chang, 2014). Alternatively, it is possible that rapidly and accurately anticipating upcoming words is strictly a sign of linguistic 'expertise' and not a mechanism by which learners gain that expertise in the first place, which suggests a sequence of events in which comprehension emerges before anticipation abilities (Christiansen & Chater, 2016; Rabagliati et al., 2016). This study aims to complement previous investigations investigating anticipation in language processing in children with relatively established language abilities(e.g., Borovsky et al., 2012). Specifically, we evaluated the developmental emergence of infants' early lexical comprehension and lexical anticipation abilities from 12 to 24 months. Our cross-sectional study aimed to determine how these linguistic abilities might co-develop during a period of rapid changes in language learning.

Our results, looking across infants at 12, 15, 18, and 24 months of age, suggest that comprehension and anticipation are closely linked over developmental time and within individuals. In this cross-sectional investigation, we found that when infants were 15 months old, our experimental methods could reliably detect their comprehension of target nouns (e.g., *cookie*), and these same measures also revealed anticipation of the target nouns (e.g., looks to the target referent while hearing informative, semantically-related words, such as *eat*). We did not see evidence for either behavior at 12 months, and we continued see evidence for both at 18 and 24 months. Moreover, we observed a positive relation between infants' comprehension and anticipation measures regardless of age, such that infants who anticipated upcoming words were more also likely to attend to the correct referent once it was named. Results also indicated a positive relation between anticipatory eye movements and vocabulary size, as in many prior studies (Borovsky et al., 2012; Lew-Williams & Fernald, 2007; Mani & Huettig, 2012). Notably, we find no evidence of reliable comprehension in the absence of anticipation which provides some evidence that anticipation is not an ability that emerges after comprehension but rather either concurrently or in support of comprehension.

Together, these findings add to a growing body of literature suggesting that anticipatory processes such as prediction and priming are potential developmental mechanisms (Borovsky et al., 2012; Fernald et al., 2008; Gambi et al., 2021; Lew-Williams & Fernald, 2007; Lukyanenko & Fisher, 2016; Mani & Huettig, 2012; Ylinen et al., 2016). The present correlational results are most consistent with a view that comprehension and anticipation abilities emerge concurrently in infancy, and therefore that the cognitive processes that allow anticipation of upcoming information—such as prediction or priming—have the potential to shape the course of early language development. Although the precise mechanisms of the observed effects remain to be determined, these findings suggest that infants may proactively allocate their attention in advance of upcoming words, and these behaviors could have implications for infants' emergent linguistic knowledge. By anticipating upcoming information, infants may gain valuable opportunities for learning as they encounter varying combinations of familiar and novel words, referents, and events during day-to-day interactions with caregivers.

These results further contribute to a broader literature investigating infants' learning mechanisms. Numerous studies indicate that infants detect statistical regularities in language and could use these regularities to learn (for review see Saffran & Kirkham, 2018). For example, Graf Estes et al. (2007) found infants could use statistical regularities to segment words from continuous speech and, importantly, could map those words to novel objects. The present findings suggest that not only can infants detect statistical regularities (e.g., that *eat* is more likely to co-occur with *cookie* than with *shoe*), but at 15 months they may also be exploiting those regularities to more rapidly identify familiar referents (e.g., using *eat* to initiate eye movements to a cookie). Thus, infants not only detect linguistic regularities but, importantly, the present findings suggest they could also use those regularities to change how they interpret incoming speech and direct their visual attention beginning around 15 months of age. Moreover, language is rich with information that infants could use to predict upcoming information. For example, a recent study by Ferry et al. (2020) found that infants learning Italian were sensitive to morphological regularities (e.g., gender and plurality) during real-time sensitive comprehension. Indeed, Mornati et al. (2022) found that infants learning Italian can indeed use the morphosyntactic feature of gender to anticipate upcoming target references when they are in their infancy. Suggest that infants might be able to use multiple cues within their linguistic stream to anticipate upcoming input and facilicate greater processing. These findings are in line with a view of learning in which anticipatory processes—including mechanisms such as prediction, priming, or expectation—support infants in refining and expanding their understanding. That is, infants may use their existing knowledge to anticipate upcoming information, which enables them to explore and discover new information (Emberson, 2017; Stahl & Feigenson, 2015).

A number of limitations remain to be addressed in order to more fully understand when and how anticipatory processes might shape the course of language development. The present investigation reveals novel correlational findings linking infants' emergent anticipation and comprehension abilities over a key period of language development. However, the current study's design and methodology also entail multiple interpretational constraints that must be overcome by future investigations. For example, like many developmental studies, sample sizes in each age group were small, leading to the relatively low statistical power, which is common in developmental psychology (Oakes, 2017). Further replication and extension of the current findings will be important to examine the robustness of our results using larger sample sizes. Moreover, this cross-sectional study does not provide precise information about when infants' language abilities emerge, nor does it directly test theoretical claims about causal relations between lexical anticipation and comprehension (e.g., Dell & Chang, 2014). A cross-sectional design allowed us to examine the emergence of infants' lexical anticipation and comprehension abilities side by side—which builds on prior studies (e.g., Borovsky et al., 2012)—but the present findings are still correlational and must be interpreted as such. A longitudinal design could aid in evaluating within-participant changes and reveal more detailed information about when and how infants' emergent language abilities arise in relation to each other. Yet, even with a longitudinal design, it would be difficult to conclusively determine the precise timing of developmental changes in infants' word knowledge or directional relations between their anticipation and comprehension abilities. In addition, this study provides some initial evidence that real-time language comprehension is not present before anticipation but it may be that a more sensitive task could detect comprehension before anticipation of those items (see further discussion on this below). Relatedly, for individual age groups, our sample sizes are too small to be well powered for small effect sizes. Future work will certainly continue to investigate this theoretically-central question with a variety of measures and approaches.

In this vein, the present study's findings raise a number of questions for further investigation: Do infants consistently anticipate upcoming words, even during the earliest stages of language development? At what point are learners' comprehension abilities robust enough to enable fast and accurate anticipation of upcoming words, and conversely, at what point are learners' anticipation abilities reliable enough to facilitate more efficient comprehension? Future studies will need to scrutinize the first moments of word learning to evaluate infants' propensities to anticipate upcoming information (both accurately and inaccurately) and to see how those propensities might evolve over time as infants' linguistic abilities improve.

Additional questions arise when explaining the null results observed for 12-month-old infants. One explanation for this finding is that the youngest infants did not robustly anticipate or comprehend words like “cookie” and therefore failed to reliably look to the target image. Comprehension estimates from WordBank (Frank et al., 2016) suggest that infants' comprehension of target nouns increases from 12 to 15 months, and the present results are consistent with these norms. However, it is also possible that our measures do not reveal the full extent of this youngest group's abilities. Prior research suggests that infants can link very familiar words with relevant visual referents by approximately 12 months of age (Bergelson & Aslin, 2017a; Huttenlocher, 1974; for review see Swingley, 2009), and some studies even suggest that infants as young as 6–9 months old can comprehend very common nouns (Bergelson & Aslin, 2017b; Bergelson & Swingley, 2012). However, the comprehension abilities of infants in these studies were relatively weak, and they became more robust with development. Why did our findings with 12-month-olds not match these prior studies? We considered the possibility that performance among the youngest age group was more variable, but exploratory analyses suggested that this was not the case (see SupplementaryMaterials). Thus, the most likely answer is that prior studies used simple sentences such as *Where's the ball? Do you see it?* (Fernald et al., 2006)? or *Look at the sock* (Bergelson & Aslin, 2017a), while our trials included multiple sentences and a larger number of words. This aspect of our experimental design enabled us to test infants' ability to use related words to anticipate downstream words, but this inherently increased complexity of the spee?ch stimuli and increased the length of the trials, which may have placed added cognitive demands on 12-month-old infants. Importantly, our measures still revealed increases in comprehension abilities of target nouns across the second postnatal year, consistent with prior work, and importantly, we revealed a corresponding emergence of anticipation of those same nouns.

Finally, the current study is focused on the relationship between anticipatory processes (prediction, priming or another mechanism) and comprehension in infants 12–24 months. As noted in the Introduction, it is beyond the scope of this paper to conclusively determine whether the mechanisms supporting these anticipatory looking behaviours are driven by one of these specific mechanisms over another. Moreover, there is a broad range of potential language learning mechanisms, and anticipation may not be an optimal strategy in every situation. For instance, given that backward statistics are more informative in some contexts, anticipation may not always be the most optimal basis for learning (Huettig, 2015; Huettig & Mani, 2016). Future studies must further evaluate when and how anticipatory mechanisms such as prediction and priming could support learning, and how these mechanisms might interact with other developmental factors, ultimately giving rise to the speed and accuracy of adult language processing. Moreover, findings of the current study may also shed some light on the development of early semantic networks. A number of findings indicate that semantic relatedness factors into infants' real-time language processing and the shape of their network of early-learned words (Arias-Trejo & Plunkett, 2009; Bergelson & Aslin, 2017a; Peters & Borovsky, 2019; Willits et al., 2013), and anticipatory mechanisms—whether top-down prediction or bottom-up priming—may connect with these developmental findings. Specifically, that there are multiple mechanisms that could explain the processing of semantically-related words and that this might have interrelated and reciprocal effects during language development.

In conclusion, the present results reveal that infants' abilities to comprehend and anticipate upcoming words emerge in tandem over the second postnatal year. We find no evidence that anticipation emerges only after a prolonged period of reliable comprehension. Rather, these developing language abilities appear to be intertwined: When infants showed reliable comprehension of familiar words, they were also able to use informative, semantically-related words to anticipate their imminent arrival. These findings are consistent with the view that comprehension and anticipation processes are tightly linked during early periods of vocabulary growth, and therefore that anticipatory processes may be mechanisms for developmental change rather than solely the consequences of development.

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CONFLICT OF INTEREST STATEMENT

The authors declare that the research herein was conducted in the absence of any relationships that could be construed as a potential conflict of interest.

DATA AVAILABILITY STATEMENT

All stimuli, experiment code, de-identified data, analysis code, and supplementary materials for this study can be accessed at Open Science Framework (OSF): https://osf.io/8txzp/?view_only=d3c06e49f45a4ea98559ebcf0e954922.

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SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

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