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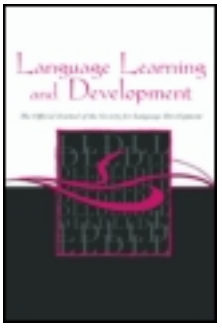

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Visual Prediction in Infancy: What is the Association with Later Vocabulary?

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Visual Prediction in Infancy: What is the Association with Later Vocabulary?

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Young infants can learn statistical regularities and patterns in sequences of events. Studies have demonstrated a relationship between early sequence learning skills and later development of cognitive and language skills. We investigated the relation between infants' visual response speed to novel event sequences, and their later receptive and productive vocabulary. Using a modified visual expectancy paradigm (VExP; Haith, Wentworth, & Canfield, 1993), we tested 6-month-old infants' speed at responding to novel but predictable contingent event sequences. In addition, parental reports and behavioral measures of infants' vocabulary were obtained at 12, 16, and 22 months. In order to estimate the separate effects of linguistic input on vocabulary, maternal speech from a play session at 12 months was analyzed for lexical diversity and quantity. Results suggest that infants' speed of responding to novel but predictable events at 6 months robustly predicted both receptive and productive vocabulary at 22 months. This relation cannot be attributed to general cognitive maturity, as measured by a standardized test (Bayley Scales of Infant Development; Bayley, 2005). Maternal input predicted additional unique variance in infant processing speed. The results suggest that infants' capacity to quickly learn and respond to sequential patterns, over and above the quality of the speech input they receive, contributes to vocabulary size in the second year.

INTRODUCTION

From the first weeks after birth, infants can learn to predict sequences of events in "noisy" social environments (Kaye, 1982). Many of the sequences infants learn involve probabilistic contingencies. A contingency is defined as a temporal relationship between two events (event A and event B) such that an occurrence of A is associated with a greater (or lesser) likelihood of B, relative to other preceding events, and within some constrained temporal parameters.

The ability to learn nonverbal contingent sequences is relevant to language development (Conway, Bauernschmidt, Huang, & Pisoni, 2010). To learn the meanings of other people's social or communicative actions (e.g., words), infants must be able to detect and learn stochastically

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predictable patterns of events within social interactions, as well as patterns of linguistic elements within utterances. Some of these patterns provide useful information for word learning; for example, parents rhythmically move objects (i.e., shaking the ball) while naming them, and this can help infants learn word-object associations (Gogate, Bahrick, & Watson, 2000).

Infant learning of novel contingencies has been studied using the Visual Expectancy Paradigm (VExP; Canfield & Haith 1991; Haith, Wentworth, & Canfield, 1993; Wentworth & Haith, 1992). In the original paradigm, infants saw a sequence of two lights turning on and off. If the sequence is simple and repetitive, infants eventually start to saccade faster toward the next location, sometimes even before that light turns on. These *anticipatory or predictive shifts* indicate contingency learning: the infant comes to anticipate the next event based on prior experience of that sequence. There is evidence that individual infants differ in their readiness to learn these sequences, and these differences are moderately stable over time. In a longitudinal study of individual differences in processing speed and contingency learning using the VExP, Canfield, Smith, Brezsnyak, and Snow (1997) found moderate stability from 6 to 12 months ($r = .49$).

Individual differences in sequence-learning skill might predict later cognitive differences: Dougherty and Haith (1997, 2002) found that infants' ability to learn simple event sequences in the VExP and the infants' response speed predicted later IQ. This extends other findings that infants' general cognitive efficiency predicts individual differences in later cognitive abilities (Rose & Feldman, 1997).

Other tests of infants' visual contingency learning show an association with cognitive processing and language skills. These tests include spatial cueing tasks (e.g., Johnson, Posner, & Rothbart, 1991; Richards & Hunter, 1997; Rose & Feldman, 1997) and preferential looking tasks (Marchman & Fernald, 2008). Additional studies suggest that individual infants' speed of auditory processing predicts later language skills and IQ (e.g., Benasich & Tallal, 2002; Newman, Ratner, Jusczyk, Jusczyk, & Dow, 2006). Finally, preferential looking tests indicate that infants' processing speed predicts individual differences in vocabulary (by parental report) in early childhood. Specifically, vocabulary and speed of spoken word recognition at 25 months of age accounted for unique variance of language and cognitive skills at 8 years of age (Marchman & Fernald, 2008).

Infants' skill at learning event sequences extends to different stimulus types in different modalities. Infants can rapidly learn sequential dependencies in speech, tones, or pictures (Aslin, Saffran, & Newport, 1998; Kirkham, Slemmer, & Johnson, 2002; Saffran, Aslin, & Newport, 1996; Saffran, Johnson, Aslin, & Newport, 1999). Little is known, however, about whether individual differences in contingency learning generalize across different kinds of information; that is, linguistic contingencies involving sounds, meanings, and uses are fundamental properties of words and therefore critical aspects of word knowledge. Receptive and productive vocabulary growth might depend on an individual's ability to learn contingencies. Yet the contingencies in visual sequences might be quite different than the contingencies related to word meanings and uses. If this is so, different learning capacities might be used to learn each type of contingency. If, alternately, visual sequence and word-meaning contingencies are learned via some shared learning processes, which are somewhat stable, then infants' responsiveness to visual sequences might predict their later vocabulary. Such a finding would enrich theories of language acquisition that stress general learning mechanisms (e.g., Carroll, 1993) rather than more narrowly tuned language-specific mechanisms.

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There is some evidence that infants' visual learning and response speed predict later language outcomes, including vocabulary size. Tamis-LeMonda and Bornstein (1989) found that visual examination and habituation measures at 5 months predicted language comprehension at 13 months. Thompson, Fagan, and Fulker (1991) also found low-to-moderate correlations between novelty preference at 5–7 months and language skills at 2 years. Thus, some kinds of individual differences in infants' visual processing predict later language skills. More recent studies have further shown that infant visual recognition measures are correlated with later cognitive and language skills (Colombo, Richman, Shaddy, Maikranz, & Blaga, 2004; Rose, Feldman, & Jankowski, 2009). Therefore, infants' attentiveness to visual stimuli can predict language skills, including vocabulary.

In addition to habituation or processing-time for static images, infants' readiness to learn and respond to novel visual sequences might predict some aspects of language development. On a biological level, contingency learning occurs via different neural pathways than habituation (e.g., Salzman, Belova, & Paton, 2005), and these pathways develop at least partly independently (e.g., Colombo, 1995; Johnson et al., 1991). Also, in language acquisition theories sequential contingency learning might play different roles in word learning and other kinds of learning. For example, in Ullman's declarative-procedural (DP) model of language acquisition (Ullman, 2001), lexical and lexicalized grammatical representations are instantiated in specialized lexical networks, and generalized syntactic "routines" are represented in other networks that encode procedural knowledge. These networks make different use of the information contained within a contingency.

However, that view treats lexical representations as "atomic" units and ignores some of the contingent aspects of word knowledge. Learning words entails learning contingencies on several levels, including speech sound sequences, sequential associations with other words and morphemes, and contextual conditions in which words are used (Deák, 2000). By this view, infants' ability to efficiently learn words depends not only on encoding speed, which influences looking-time, but also event contingency learning ability, which influences the speed of anticipatory looking.

Recent work with adults as well as infants suggests that there are correlations between nonverbal contingency learning and language skills. Conway and colleagues found that adults' implicit learning skills were directly related to language skills (Conway et al., 2010). Additionally, Misyak, Christiansen. and Tomblin (2010) synthesized evidence indicating that adults' statistical learning skill contributes to their language skills. In a recent study, Shafto and colleagues found that 8.5-month-olds infant's ability to learn visual sequences was correlated with their concurrent receptive vocabulary size and their gesture comprehension skills five months later (Shafo, Conway, Field, & Houston, 2012). However, no study has specifically investigated whether *visual sequence response efficiency* during infancy predicts later receptive and productive vocabulary size.

Even if infants' visual event-contingency response speed does predict early vocabulary and word learning, it is likely to be only one of many predictors. Another known predictor of early vocabulary size is the quality of parents' language to the infant (Hart & Risley, 1995; Hoff, 2003; Huttonlocher, Haight, Bryk, Seltzer, & Lyons, 1991). Several studies have found that the quantity and diversity of maternal speech—even from as little as a 10-minute sample—is a strong predictor of infants' later vocabulary (Rollins, 2003). Because of this strong predictive relationship, it is important to assess maternal input (types/tokens) as well as infants' contingency response

speed. This is because if infants' visual-contingency response speed is related to vocabulary, it might be mediated by a third factor. That factor might be a heritable cognitive trait that affects both maternal speech rate *and* learning speed (see Luciano et al., 2001; Rowe, Jacobson, & Van den Oord, 1999). Alternately, infants who respond more quickly to events might tend to elicit more speech from parents. In either case, it is necessary to separately assess the contributions of maternal speech and infant response speed to later vocabulary. Assessing both factors helps to determine whether they are independent predictors.

The primary purpose of the present study was to examine the relation between infants' speed of responding to novel but predictable visual event sequences at 6 months of age and their vocabulary size during the second year, operationalized as (1) receptive vocabulary at 12, 16, and 22 months of age and (2) productive vocabulary at 16 and 22 months. Our secondary purpose was to explore whether this relation was mediated by maternal input factors, or by possibly interrelated, heritable cognitive factors.

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METHOD

Participants

As part of a larger longitudinal study on social-cognitive development (Deák, Triesch, Krasno, de Barbaro, & Robledo, 2013), the current data include 32 infants at 6 months of age (17 m, 15 f, mean age = 189 days, range = 175–209). The participants were primarily English-speaking, Caucasian infants and mothers from middle socioeconomic-status (SES) homes in the greater San Diego area. Average age of the mothers was 31.8 years (range = 26–42), and their average length of formal education was 16 years (range = 12–21). All infants were full-term, with no reported sensory, developmental, or medical problems. The participants were a sample of convenience, recruited through announcements and flyers at local classes, day-care centers, and playgroups in San Diego, California. Recruitment and testing procedures adhered to guidelines for ethical treatment of research participants, and were approved by the Institutional Review Board at the University of California, San Diego.

Materials and Procedures

At their six-month visit, infants had visited the lab on two prior occasions and participated in tests in the setting described below, with the same experimenters. Thus, individual differences in reactivity to a novel environment were likely attenuated. At the 12-month session when maternal speech was recorded, the researcher had previously visited the families seven times, and mothers and infants were comfortable with her presence.

Visual Sequence Response Task. An experimenter (E1) first explained the task to the mother and obtained informed consent. Mother and infant were brought into a dimly lit testing room. The infant was seated on the mother's lap facing a projection screen (Figure 1). Mothers wore black glasses and headphones so that they were blind to the stimuli. A Canon GL-1 video

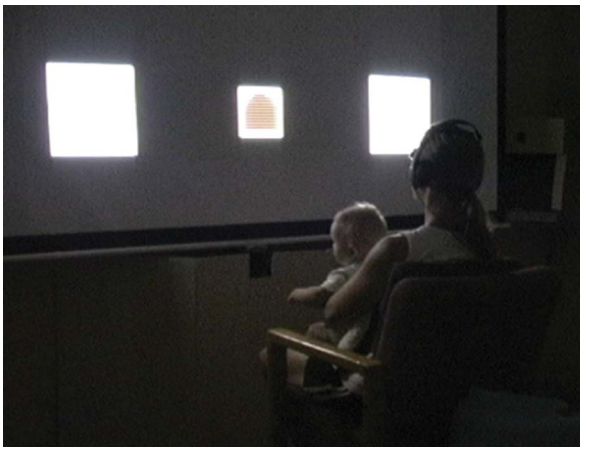

FIGURE 1 Infant sitting on mother's lap, viewing the three image locations, with a center cue displayed. (Color figure available online.)

camera captured the infant's face. Another experimenter (E2) in an adjacent control room monitored the infant's face, and began the program to present stimuli and record infants' responses.

A modified version of Haith's VExP task was programmed in VisualBasic (available from Gedeon Deák). The task presented stimuli on a screen approximately 90 cm from the infant's face. First, an orientation stimulus (8° visual angle) of an animated, colorful abstract object, paired with a stimulating sound, was shown at center of the screen. This ensured that the infant was oriented to the cue stimulus. Second, one of two cue stimuli, complex geometric shapes (15°) with distinct colors and patterns, was presented at the center. Third, an attractive "outcome" target animation was presented at the left or right (15°). Targets were distinct, appealing, rotating shapes paired with unique sounds. The infants saw two different cues and two different targets repeatedly over 30 trials. All stimuli were novel. Cue and target stimuli are shown in Figure 2.

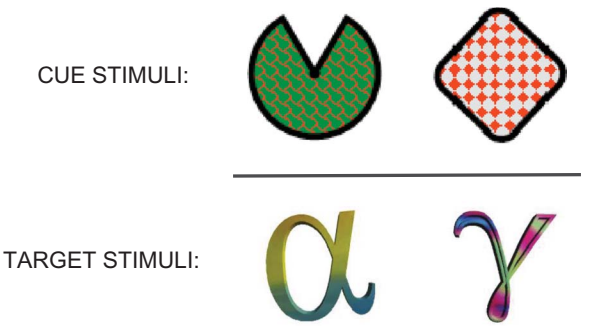

FIGURE 2 Top: Examples of cue stimuli (presented at center). Bottom: Examples of animated target stimuli (presented to left and right). (Color figure available online.)

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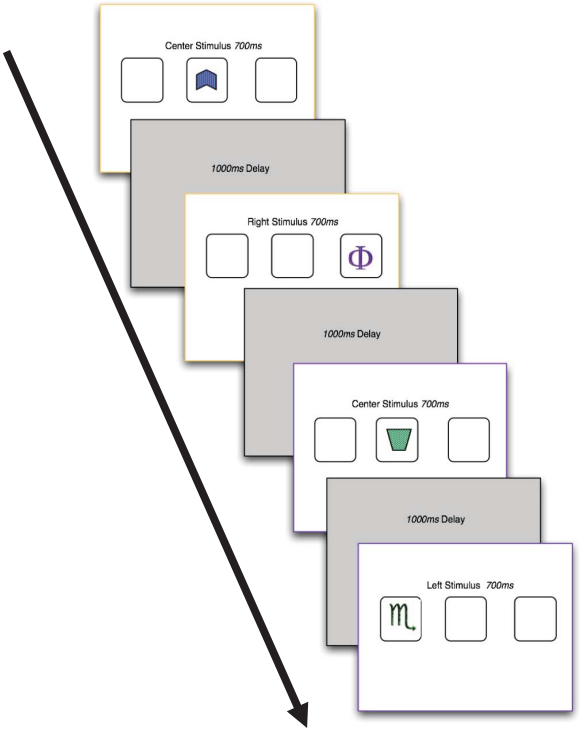

FIGURE 3 Timing and sequence of stimuli order. (Color figure available online.)

In each trial the orientation stimulus was presented for one second. If the infant did not look, E2 made the orientation stimulus repeat until the infant looked. Then one of two cue stimuli, C_A or C_B, appeared for 700 ms. This was followed by a one-second delay. Finally one of two outcome target animations, T_A (left) or T_B (right), appeared for 700 ms. The trial sequence is shown in Figure 3. Center cues were presented in quasi-random order with no more than two successive repetitions of either cue. In the test trials stimuli C_A always preceded T_A, and C_B always preceded T_B. Infants could learn that each cue predicted a different target on the left or right. Infants who learned the cue-to-target associations could shift gaze faster to the correct location, sometimes before the target began or just as it was starting (meaning the infant had already planned the saccade). These are *predictive* shifts. A video of the infant's face, showing the reflection of the stimuli on the infant's corneas, was captured to a computer for off-line analysis.

Vocabulary Measures. A parent report measure of vocabulary skill, the MacArthur-Bates Communicative Developmental Inventory-Short Form, Level I (MBCDI; Fenson et al., 2000), was completed when the infants were 12, 16, and 22 months of age. The Infant Short Form version is a checklist with 89 representative words selected from the long-form MBCDI, which provides a close estimate of full MBCDI scores (Fenson et al., 2000). The MBCDI-Short Form was used for the convenience of families who were part of a larger longitudinal study that entailed a substantial time commitment (the long form can take up to 45 minutes to complete). For each

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word on the checklist, parents report whether their child understands it, understands and produces it, or neither. Forms were scored by hand and checked for accuracy by a second researcher. Scores indicate the total raw numbers of words comprehended and total number produced. Because production scores at 12 months tend to show large floor effects, a limited range, and a positive skew, they were not analyzed.

In addition to parent reports of vocabulary at 12, 16, and 22 months, for convergent validity infants completed a behavioral measure of receptive vocabulary, the Computerized Comprehension Test (CCT; Friend & Keplinger, 2003, 2008), at 22 months. In the CCT, pairs of photographs of prototypical stimulus exemplars are presented on a touch-screen, and the infant touches one of each pair of images in response to a prompt from an experimenter. Prompts include a target vocabulary word (e.g., "Where is the shoe?" "Touch the shoe!"). Touching the correct target produces a reinforcing sound that maintains infants' interest and compliance. The words are nouns, adjectives, and verbs from the MBCDI-short form, stratified for age-of-acquisition. Each of the 41 words is presented twice, with left-right positions of the image pairs reversed to ensure that infants' choice of pictures is based on the word prompt, and not a random response (see Friend & Keplinger for details.)

Cognitive Maturation. By assessing infants' general cognitive skill, we can verify whether heritable cognitive factors mediate any relation between infant event contingency response speed and vocabulary. To estimate infants' general cognitive maturity, they completed a standardized, broad measure of cognitive status (Bayley Scales of Infant Development: BSID-III; Bayley, 2005) at 12 months of age (mean = 372 days). The BSID-Cognitive scale includes a variety of brief, age-normed behavioral tests believed to indicate infants' general cognitive developmental status. The scores allow us to remove any effects of general cognitive maturity from correlations between event-contingency response speed and measures of vocabulary. Importantly, the BSID-III-Cognitive scale does not include any tests of contingency learning, or response speed, or vocabulary. Thus, there are no confounding effects of shared measurement error in using BSID-Cognitive scores to partial out general cognitive skills.

Averages and Standard Deviations for MBCDI receptive and productive vocabulary size, CCT accuracy, and BSID-III Cognitive scores are shown in Table 1.

TABLE 1
Means and *SDs*: BSID-III Cognitive; MBCDI at 12, 16, and 22 Months

Dependent Variable	*N**	*Means (SD)*	*Range*
BSID (Bayley) 12-month Cognitive	32	109.37 (12.8)	85–135
12-month MB-CDI: Comprehension	26	25.88 (17.2)	4–68
16-month MB-CDI: Comprehension	24	45 (22.09)	8–89
16-month MB-CDI: Production	24	18.41 (15.76)	0–55
22-month MB-CDI: Comprehension	24	70.91 (17.87)	35–89
22-month MB-CDI: Production	24	48.2 (22.39)	7–84
CCT Correct Touches	21	29.62 (3.27)	24–38
CCT % correct on attentive and completed trials	21	72.24 (.07)	58.53–92.68

**Note.* Although extensive attempts were made to ensure that MBCDIs were returned at each age, some families did not return the forms, resulting in slightly different *N*s across months.

FIGURE 4 Example of infant and mother in free play interaction at 12 months, from which maternal speech counts were derived. (Color figure available online.)

Maternal Speech. To assess and control for possible caregiver effects on vocabulary, (i.e., quantity and diversity of lexical input), maternal language to infants during a play session was transcribed. During the visit to the dyad's home when the infants were 12 months old, infants and mothers engaged in approximately 12 minutes of unscripted ("free") play. Dyads were video-recorded while playing on the floor with a set of infant toys provided by the experimenter (Figure 4). Thus, objects that served as potential referents of maternal speech were controlled across dyads. Maternal speech was transcribed off-line using ELAN software (http://www.lat-mpi.eu/tools/elan/; Sloetjes & Wittenburg, 2008).

Visual Response Coding

Infant looking (left, center, right, or off-task) was coded offline frame-by-frame (30 fps) using Mangold Interact software. Coders were blind to target location, cue identity, and specific hypotheses. LED lights superimposed on the video indicated the onset of an event, without indicating which specific cue or target had appeared. Infant looking was coded for location and saccade response time (RT) following the cue onset. Based on prior work (Dougherty & Haith, 1997; Marchman & Fernald, 2008; Rose & Feldman, 1997), we examined infants' overall response speed when watching predictable events and infants' speed when they showed that they had anticipated the next target event. The latency of all saccades to correct and valid target locations were coded to derive an overall Average Response Time (RT). Each RT was the latency from cue onset to the initiation of the saccade (whether the look was predictive or not). To specifically assess infants' speed when they had anticipated where to look next, we calculated the mean Predictive Response Time. Predictive saccades were those that began up to 180 ms after the target onset. This threshold was based on findings that infants require approximately 180 ms to plan and initiate a saccade (Canfield et al., 1997; Gredebäck, Örnkloo, & von Hofsten, 2006). Only valid and correct trials were analyzed: the infant had to be looking at the center cue when it came on, and then make a saccade to the left or right target location before the trial ended.

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RESULTS

Infants completed an average of 17.5 ($SD = 5.3$) valid and correct trials (range = 4–29). (Invalid or incorrect trials were not included in the analysis.) Of these trials, 23.4% ($SD = 12\%$) were predictive (i.e., anticipatory). The overall average RT for all correct and valid trials (RT_{avg}) was 1.77s ($SD = .17$). Infants' mean response speed for predictive looks (RT_{pred}) was 1.34s ($SD = .31$) following the cue onset (recall that the target began 1.7s after the cue) (see Table 2). To control for test-wise inflation of Type I error, critical alpha level was set at $p < .03$, and values between .03 and .05 were considered marginal.

Response Speed and Receptive Vocabulary

Infants' response speed predicted their later receptive vocabulary. Overall speed of responding to contingent visual targets at 6 months predicted MBCDI-receptive vocabulary at 22 month, $r(21) = -.512$, $p = .018$. Additionally, RT_{avg} was correlated with infants' CCT scores, $r(22) = -.499$, $p = .036$. Thus, both parent-report and behavioral measures at 22 months were predicted by 6-month RT_{avg}. However, RT_{avg} was not statistically significantly correlated with receptive vocabulary at 12 and 16 months, though the correlations were in the hypothesized direction ($r = -.35$ and $-.26$ at 12 and 16 months, respectively).

There were similar relations between receptive vocabulary and infant's response speed in predictive trials (RT_{pred}). RT_{pred} was correlated with MBCDI vocabulary at 22 months, $r(22) = -.467$, $p = .029$, and with CCT scores at 22 months, $r(19) = -.447$, $p = .055$ (see Table 3). RT_{pred} was not reliably correlated with receptive vocabulary measures at 12 and 16 months, but again the correlations were in the hypothesized direction ($r = -.29$ and $-.25$, respectively).

TABLE 2
Means and *SDs*: Response Speed Measures at 6 Months

Measure	*N*	*Means (SD)*	*Range*
Valid trials	32	17.5 (5.3)	4−29
RT predictive	30	1.34 (.31)	.45−1.86
RT average	28	1.77 (.17)	1.28−2.01

TABLE 3
Simple Correlations Among Response Speed and Receptive Language Measures (MBCDI-Short form and CCT)

	MBCDI-12 Comp	*MBCDI-16 Comp*	*MBCDI-22 Comp*	*CCT-22*
RT-avg	−.355, p = .114, n = 21	−.266, p = .23, n = 22	−.512*, p = .018, n=21	−.499, p = .036, n = 21
RT-pred	−.299, p = .29, n = 23	−.254, p = .23, n = 24	−.467*, p = .029, n=22	−.447, p = .055, n = 19

Note. $^{*}p < .03$.

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TABLE 4
Simple Correlations Among Response Speed and Productive Language Measures (MBCDI-Short form)

	MBCDI-16 Prod	*MBCDI-22 Prod*
RT-avg	−.219, p = .32, n = 22	−.569*, p = .006, n = 22
RT-pred	−.218, p = .3, n = 24	−.517*, p = .012, n = 23

Note. $^*p < .03$.

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Response Speed and Productive Vocabulary

Average speed at 6 months, RT_{avg}, predicted productive vocabulary at 22 months, $r(22) = -.569$, $p = .006$. Thus, faster infants tended to be more productive talkers at 22 months. RT_{avg} was not statistically significantly correlated with productive vocabulary at 16 months, but the correlation was in the hypothesized direction ($r = -.219$); see Table 4.

Response speed in predictive trials (RT_{pred}) reliably predicted productive vocabulary at 22 months $r(23) = -.517$, $p = .012$. RT_{pred} was again not statistically correlated with productive vocabulary at 16 months, but again the correlation was in the hypothesized direction ($r = -.218$).

Across measures, 6-month visual response speed was a reliable and moderate predictor of vocabulary at 22 months but was not a reliable predictor at 12 or 16 months. The stronger relation to later vocabulary may reflect the increasing stability and/or reliability of infant vocabulary measures during the second year. It might also reflect improved test sensitivity to vocabulary differences at 22 months than at 12 or 16 months (Fenson et al., 1994).

Overall response speed was determined by infants' response speed in predictive trials: the two measures were strongly correlated, $r = .915$ ($p < .001$). Thus, variability in response speed was accountable to infants' speed to saccade to the target on trials when they correctly predicted its location from the cue. This suggests that infants' efficiency to process the implications of the cue-stimulus, once it had acquired a sequential cue value, was the cognitive ability that predicted later vocabulary. By contrast, infants' RT in "reactive" trials—that is, when they shifted gaze to the target more than 180 ms after it appeared—showed no statistically reliable correlations with later vocabulary, although most correlations were in the expected direction.[1]

Maternal Input and Infant Vocabulary

Our secondary question concerned the contribution of maternal input to later vocabulary. Most mothers' ($n = 29$) 12-month home-play speech samples were audible and long enough (approximately 10–12 minutes) to be transcribed and entered in the analysis. Because each dyad's free-play session varied somewhat in duration, we used rate measures; namely word tokens per minute and word types per minute. Mothers produced an average of 68.1 tokens/minute ($SD =$

[1] RT_{pred} was not correlated to the proportion of trials in which the response was predictive ($p = .85$).

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25.1, range = 31.9–159.6), and an average of 16.5 types/min (SD = 5.4, range = 5.2–39.0). Type and token rates were highly correlated, $r(29) = .902$, $p < .001$.

There were no significant correlations between maternal type or token rate and MBCDI receptive or productive vocabulary scores at any age. This might seem surprising given the findings of Hart and Risley (1995) and others, which suggest an association between maternal speech input and vocabulary development in infants. However, the association in Hart and Risley's data was strongly mediated by SES. The present sample was relatively homogeneous, with no high-risk or low-SES families. This homogeneity might have attenuated the correlation between maternal speech and infant vocabulary. An alternative possibility is that the MBCDI short form is less related than the long form to maternal input. However, previous work shows a high correlation between the short and long forms (Fenson et al., 2000). We found moderate between-age correlations in receptive MBCDI scores (range r = .41–.57), suggesting that the present vocabulary measures were estimating some stable underlying variable.

We next explored how infant response speed and maternal input are related. Type rate was correlated with overall looking speed, RT_{avg}, $r(25) = -.443$, $p = .027$. That is, mothers of faster infants used more diverse vocabulary six months later. Nonetheless, when maternal type-rate was removed, the correlation between RT_{avg} and receptive vocabulary at 22 months remained significant, $r_{part}(16) = -.480$, $p = .044$, as did the correlation with productive vocabulary at 22 months, $r_{part}(16) = -.491$, $p = .039$.[2]

Infant Response Speed and Cognitive Skills

We considered the possibility that the correlation between infant response speed and vocabulary is mediated by infants' general cognitive maturity. There were no significant correlations between response speed at 6 months and BSID-III-Cognitive scores at 12 months.

There were marginally significant correlations between BSID-Cognitive scores and 12-month receptive vocabulary, $r(26) = .416$, $p = .034$, and productive vocabulary, $r(26) = .379$, $p = .056$. However, there were no significant correlations with 22-month vocabulary scores. Further exploratory analyses showed that when BSID scores were removed, the relation between 6-month response speed and 22-month vocabulary remained significant.

DISCUSSION

The purpose of this study was to investigate whether infant speed of anticipating contingent visual sequences at 6 months predicts vocabulary at 12, 16, and 22 months. We also tested whether this correlation is due to moderating variables of maternal input or to general infant cognitive abilities. The results provide some answers to these questions and contribute to a growing body of evidence

[2]In supplemental analyses we also explored whether maternal education moderated the relation between infant anticipatory looking speed and later vocabulary. Maternal education did not correlate with infant looking speed ($RT_{pred,}$ r = .297, p = .125; $RT_{avg,}$ r = .156, p = .446) or vocabulary (22 month comprehension, r = .093, p = .672; 22 month production, r = .016, p = .941). Also, when maternal education was removed from the correlations between RT_{avg} and 22 month comprehension ($r_{part}(17) = -.560$, $p = .013$) and production ($r_{part}(17) = -.532$, $p = .019$) remained significant.

showing how infants' early cognitive processing capacities contribute to developing language and communication skills.

Infants' speed to correctly saccade to a contingent visual event was a predictor of their vocabulary at 22 months, as assessed by parental report and by a behavioral measure. This suggests that contingency learning and response speed, even in a different modality (i.e., visual), reflects individual differences in some capacity to learn sequential dependencies that is broad enough to encompass word learning. Although it has been shown that infants can learn novel event-sequential probabilities involving a variety of stimulus types such as phonemes, syllables, tones, or colored shapes (Kirkham et al., 2002; Saffran et al., 1996, 1999), there is limited evidence that individual infants' sequence-learning and anticipation speed is related to later language skills. However, such a relationship is validated by a recent study (Shafto et al., 2012).

Shafto and colleagues (2012) found a significant relationship between sequence learning and parent-reported receptive vocabulary at 8.5 months of age. The study also found that sequence learning at 8.5 months predicted parent-reported gesture comprehension at 13.5 months but not parent-reported receptive or productive vocabulary at 13.5 months. Complimentary to Shafto et al.'s results, we found no statistically significant correlation between sequence response speed at 6 months of age and parent report of receptive or productive vocabulary at 12 or 16 months. However, we did find a significant relationship to vocabulary measures taken later, at 22 months. This was found for both receptive and productive vocabulary measures. The weaker relationship of 6-month response speed to earlier vocabulary might be due to the lower variability of vocabulary at 12 and 16 months, when most infants are using few words (Fenson et al., 1994), than 22 months. Alternately, it might be due to higher measurement error at 12 and 16 months, when it is probably more difficult for parents to judge whether or not their infant knows any given word. Regardless of the reasons, the current results are among the few to discover a correlation between some nonverbal (i.e., visual) processing ability and later language outcomes, using converging measures.

These results are consistent with previous findings that individual differences in infants' visual processing predict later vocabulary and other language skills. For example, some looking-time measures during the first year predict later vocabulary (e.g., Bornstein & Tamis-LeMonda, 1989; Bornstein et al., 1992). However, those studies did not account for other factors that have since been shown to predict vocabulary. For example, within-family correlations in Verbal IQ seem to be mediated by both genetic and environmental factors (Posthuma, de Geus, & Boomsma, 2001; Rowe et al., 1999). Also, receptive vocabulary is correlated with broader cognitive abilities (Sattler, 1992). Thus the correlation between infants' predictive response speed and later vocabulary might be mediated by a diffuse cognitive phenotype that is related to family traits.

However, our data do not support this interpretation, because the correlation was not mediated by either maternal input measures or by infants' BSID-Cognitive scores. Given that previous studies (Doughtery & Haith, 1997; Rose & Feldman, 1997) reported associations between speed measures and infant development scales, this negative result might seem inconsistent. However, the BSID-Cognitive test is an untimed test of a wide range of cognitive and behavioral achievements but does not include items that specifically focus on sequence learning or response speed. By contrast, the visual sequence task is a focused measure of response speed in sequence learning. Thus, the two tests measure different abilities. Also, previous versions of the BSID folded language and cognitive items into a single "mental" scale, whereas the BSID-III separates those items into distinct scales. The correlation found in previous studies might have been driven by

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language items in the mental scale, which have now been moved. Finally, there was a 6-month gap between the measures, and intra-individual correlations could be attenuated by varying developmental processes across this interval. These reasons might explain why the BSID-III Cognitive scale at 12 months was not related to processing speed or sequence learning.

Additionally, unlike previous findings (Hoff, 2003; Rowe, 2008), maternal language quantity and diversity was not related to infants' reported vocabulary. This might be due to the limited range of maternal education and socioeconomic status in our sample. It would be interesting to replicate this study in a more culturally and socioeconomically diverse sample. It is also possible that maternal speech input factors other than type and token rate might better mediate the relation between infants' contingency learning speed and their later vocabulary size. We are currently exploring a wider range of maternal speech variables as they relate to infant language and cognitive outcomes.

Our work leaves open some theoretical questions. Average response speed was the best overall predictor of vocabulary, suggesting a domain general skill that contributes to later language. Yet this relationship was carried by infants' response speed on predictive trials, that is, their readiness to act upon newly learned contingencies. By contrast, response speed when infants reacted to a stimulus after it appeared did not predict later vocabulary. Thus, one hypothesis is that readiness to respond to recently noticed contingencies also contributes to infants' ability to notice contingencies between a spoken word and other regularities that might indicate the word's meaning (e.g., what possible referents were present; what were speakers concurrently attending to or doing). It would be useful in future studies to assess infants' response speed to different kinds of predictable events, relative to correct versus incorrect anticipations. It would also be informative to measure response speed in several kinds of tasks, to determine whether efficiency of processing in general, or specifically in sequence-learning and anticipation tests, predicts the development of language learning. Finally, it would be informative to assess a wider range of developing language skills, to determine whether anticipatory response speed predicts word learning in particular, or a broader range of language abilities.

The results add to a growing body of research revealing the relations between nonverbal processing abilities in infancy and later language outcomes. It complements a recent related study (Shafto et al., 2012) by showing a relation to later vocabulary, and by ruling out plausible mediating relationships with maternal speech input quantity and diversity, and with infants' general cognitive maturity. Thus, the results suggest that infants' speed to learn and respond to novel contingent sequences reflects a learning capacity that influences later vocabulary skill. This is a promising direction for future research into sources of individual differences in language learning, including learning impairments (e.g., Fernald & Marchman, 2012). It also suggests new questions about the underlying learning mechanisms that contribute to individual differences in early vocabulary.

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