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Contingencies Between Infants' Gaze, Vocal, and Manual Actions and Mothers' Object-Naming: Longitudinal Changes From 4 to 9 Months

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ABSTRACT
Infants' early motor actions help organize social interactions, forming the context of caregiver speech. We investigated changes across the first year in social contingencies between infant gaze and object exploration, and mothers' speech. We recorded mother–infant object play at 4, 6, and 9 months, identifying infants' and mothers' gaze and hand actions, and mothers' object naming and general utterances. Mothers named objects more when infants vocalized, looked at objects or the mother's face, or handled multiple objects. As infants aged, their increasing object exploration created opportunities for caregiver contingencies and changed how gaze and hands accompany object naming over time.

Introduction

Q1 To acquire language, infants must solve the word-to-world mapping problem, associating the language they hear with concurrent nonlinguistic experiences. Previous work has shown that features of parents' speech to infants, including total number of word tokens and mean length of utterance, predict their vocabulary as toddlers (Hart & Risley, 1995; Hoff, 2003). In addition to speech quantity, the timing and nonverbal context of caregiver speech are features that correlate with early language development. Critically, infants are not merely passively exposed to a stream of words and percepts. Rather, infants' self-generated exploratory activity directly and indirectly affects the structure of their experience with language. Specifically, some actions might elicit different amounts or types of caregiver speech. That is, caregivers might help structure the infant's language input by monitoring infants' activity and producing speech contingent on infant's engagement with objects and people. Over the course of development, therefore, infants' developing motor abilities might influence their language development by shaping the non-verbal context that accompanies caregiver speech or by giving caregivers increasing opportunities to respond to infant actions. In the current report, we examine the temporal dynamics of caregiver speech, and accompanying non-verbal actions, during unscripted mother-infant interactions. By following infants and mothers longitudinally from 4 to 9 months, we describe changes in these dynamics during the first year. Specifically, we examine how infants' actions elicit maternal speech in general, and object naming in particular, because object nouns dominate infants' first word-world associations (Gentner, 1982; but see Tardif, 1996) which Q2 for many common objects are established by 9 months (Bergelson & Swingley, 2011). In the following section, we detail what is known from previous studies regarding the features of mother–infant interaction that shape infants' language experience and development.

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Color versions of one or more of the figures in the article can be found online at www.tandfonline.com/HDVN.

Contingent responsiveness

An important feature of infants' early interactions with caregivers is the timing and appropriateness of caregiver actions relative to infant actions. This has been described in the literature as caregiver sensitivity, responsivity or contingency. Caregivers respond contingently to infants' behaviors from very early in infancy: for example, infants and caregivers engage in sequences of mutually contingent patterns of looking, smiling, and vocalizing by 1 to 3 months or earlier (Kärtner et al., 2008; Kaye & Fogel, 1980).

Many previous studies have described caregiver responsiveness in qualitative terms, with features such as "appropriateness" or consistency with the infants' ongoing activity or attention (e.g., Kochanska & Aksan, 2004). Others have characterized the frequency and timing of specific responses to infants' actions. For instance, infants and mothers engage in vocal turn-taking (Snow, 1977), and mothers also respond contingently to infants' object-exploratory actions (Bornstein, Tamis-LeMonda, Hahn, & Haynes, 2008). By 1 year of age, infants can elicit object naming from parents by object exploration (Wu & Gros-Louis, 2014b, Yu & Smith, 2012) and by explicit gestures (Goldin-Meadow, Goodrich, Sauer, & Iverson, 2007; Olson & Masur, 2011, 2013). At 14 months, Tamis-LeMonda, Kuchirko, and Tafuro (2013) observed that mothers contingently responded to infants' object exploration actions by handling the objects themselves and by producing more referential language. Such specific caregiver responses to infants' actions might impact specific developmental outcomes, including language development (Tamis-LeMonda, Kuchirko, & Song, 2014).

A large body of evidence suggests that infants learn from contingently presented information. Two-month-olds will direct social actions to a mobile that moves in response to their head movements (Watson, 1972), and even by 2 weeks infants can learn to modify their sucking rate around their mother's activity during breastfeeding (Kaye & Wells, 1980). Caregivers' contingent responses to their infants also matter specifically for language learning. For example, Tamis-LeMonda, Bornstein, and Baumwell (2001) found that maternal responsiveness at 9 and 13 months positively predicted toddlers' language development. Q3 Similar correlational findings have been reported elsewhere (McGillion et al., 2014, Gros-Louis, West, & King, 2014, Wu & Gros-Louis, 2014a, 2014b). Certain patterns can specifically facilitate prelinguistic vocal production and word learning. For example, Goldstein and Schwade (2008) found that if adults vocally responded to 9-month-olds' vocalizations, the infants' vocalizations became more advanced, incorporating phonological elements from the adults' responses. Moreover, 12-month-olds tended only to learn object names that were presented contingent on the infant vocalizing while looking at the object (Goldstein, Schwade, Briesch, & Syal, 2010). In addition, if mothers respond contingently to infants' manual gestures by "translating" the gestures into words, infants are more likely to learn to produce those words (Goldin-Meadow et al., 2007; Masur, 1982; see also Dimitrova, Özçalışkan, & Adamson, 2016). Other research has focused on caregivers' responses that match or "follow in" to infants' focus of attention (Tomasello & Farrar, 1986). For example, caregivers' tendency to produce speech acts related to infants' focus of attention at 9 months predicted infants' subsequent language comprehension (Rollins, 2003).

In the current study, we investigated potential longitudinal changes in the action contingencies that shape infants' language input across the first year. Bornstein et al. (2008) longitudinally followed mothers' verbal responses to infants' vocalizations and object exploration at 10, 14, and 21 months, and found specificity between infant behaviors and maternal response types, as well as changes in overall frequencies of infant behaviors and maternal response types with age. However, mothers' rates of response to infant behaviors were generally stable across ages. We extended this approach to a younger age group, describing contingencies between infants' gaze, hand, and vocal actions and mothers' speech between 4 and 9 months. Specifically, we investigated the frequencies of different infant behaviors and maternal responses over that period, and any changes in the contingent relations between them.

Infant motor development

Infants' motor activity directly and indirectly affects the structure of their experience with language (Iverson, 2010). Infants' object manipulation and gaze directly influence their sensory experience during caregiver speech (Yoshida & Burling, 2013). Additionally, infants' actions—looking, handling, and vocalizing, among others—can indirectly influence their experience by eliciting caregiver actions. Therefore, advances in infants' motor skills are likely to change their language experience in two ways: by shaping their sensory (especially visual and haptic) experience during speech, and by eliciting different speech from caregivers. For example, 13-month-olds who have begun walking elicit more action directives in response to their object bids than do crawling infants (Karasik, Tamis-LeMonda, & Adolph, 2014). At 8 months, crawling infants elicit more prohibitions than noncrawling infants (Zumbahlen, 1997). During the first year, infants' growing motor proficiency in manipulating objects might also trigger changes in caregiver speech. Coordination of gaze and manual activity changes rapidly during the first year as infants become more proficient at reaching, manipulating objects, and flexibly directing their gaze and hands to things in the world (Fagard & Lockman, 2010; Rochat, 1989; Ruff, 1984; von Hofsten, 1991) and coordinating manual and vocal activity (Iverson & Fagan, 2004). Previous work in our lab has shown that in dyadic toy play interactions, infants decrease their object gaze time and increase object handling across the first year (de Barbaro, Johnson, Forster, & Deák, 2015). Additionally, infants increasingly manipulate two objects simultaneously (de Barbaro et al., 2015) and in more complex ways (de Barbaro, Johnson, & Deák, 2013). We hypothesize that these and other changes in object manipulation and other motor skills will affect the language that infants hear by increasing how often they produce behaviors that elicit contingent speech. Opportunities to learn language through social contingencies might thereby expand as infants' behavioral skills develop and diversify.

Correlates of caregiver speech

In addition to being produced contingently on infant actions, caregiver speech is also "packaged" with regularities in ongoing sensorimotor activity (Meyer, Hard, Brand, McGarvey, & Baldwin, 2011). Infants' experiences unfold in social exchanges in which both partners structure the visual and auditory scene through multiple behavioral modalities, including vocalizations, gaze, and manual activity (Deák, Krasno, Triesch, Lewis, & Sepeta, 2014; de Barbaro et al., 2015; Yu & Smith, 2013). Mapping words to referents is likely to be facilitated by concurrent sensory and motor experiences around the times when objects are named. For example, 18-month-old children's learning of a novel object word is predicted by the size of the object in their visual field when it is named (Yu & Smith, 2012).

Some of the regularities in activity around caregiver speech are provided by caregivers' paralinguistic actions. During infants' first year, caregivers' object-name productions are embedded in multimodal behavioral complexes featuring synchronous speech and object motion (Gogate, Bahrick, & Watson, 2000; Gogate, Maganti, & Bahrick, 2015; Matatyaho & Gogate, 2008). In one study, mothers taught 6- to 8-month-old infants two novel object words. Only infants who attended to their mothers' synchronous speech and object motion showed a higher proportion of anticipatory or first looks to the named object after a 3-minute teaching period (Gogate, Bolzani, & Betancourt, 2006). Thus, production of multimodal communicative actions by caregivers contributes to early word learning. However, such studies of caregivers' object naming with infants under a year of age have not addressed how infants' actions might contribute to the "packaging" of speech with ongoing activity. We therefore investigated, across the age range studied, associations between caregiver speech and either infant or caregiver actions occurring before, during, or after speech. We expected that these associations would increasingly involve infants' manual activity at the expense of mothers' as infants became more active participants in the interaction.

Present study

The present study documents changing contingencies between infant exploratory and social behaviors from 4 to 9 months, and their mothers' vocal responses including utterances about objects, recorded within a longitudinal sample of unscripted toy-play interactions. We focused on the following questions: What infant gaze, hand, and vocal actions predict maternal speech in general, or object naming in particular? Do age-related changes in infants' object exploration lead mothers to produce more predictable object-naming or overall speech? Across the age range studied, what sequences of infant and mother manual or visual engagement with objects tend to accompany object naming? We predicted that mothers' verbal responses to infants' behaviors would be specific and relatively stable. We also predicted that, with increasing age, object naming would become more strongly associated with infants' own manual activity rather than that of the mother. Finally, we predicted that infants' increasingly differentiated manual activity would strengthen contingencies by giving mothers of older infants more opportunities to respond.

Methods

Participants

Participants were 42 mother–infant dyads (20 female) from a longitudinal study of infant social development (Deák, Triesch, Krasno, de Barbaro, & Robledo, 2013). Participants were recruited as a sample of convenience from the greater San Diego area. Mothers' mean age upon recruitment was 32.1 years (range = 21–42) and they had completed a mean of 16.1 years of formal education (range = 12–21). Twenty-nine infants were Caucasian, 2 were Asian, 4 were Hispanic, 5 were other or multiple races, and 2 did not report their ethnicity. None of the infants had any neurological, cognitive, or sensory deficits, according to parental report. Six additional participants dropped out of the longitudinal study. An experimenter visited the participants' home each month between 4 and 9 months, and again at 12 months (participants also visited the laboratory to complete various tasks every month; those data are reported elsewhere, e.g., Deák, 2015; Ellis, Gonzalez, & Deák, 2014). Data from the 4, 6, and 9-month home sessions were analyzed for this study. Participants were observed within 2 weeks of the infant's 4, 6, or 9-month birthday (five sessions had to be rescheduled; these were completed before the infant's next month's birthday. Infants' mean age was 125 days at the 4-month session (range: 113–142), 186 days at the 6-month session (range: 175–211), and 277 days at the 9-month session (range: 260–300). Due to infant fussiness or equipment failure, one dyad did not complete the 4-month session, two did not complete the 6-month session, and one did not complete the 9-month session; however, these dyads' data from the remaining sessions were included in analyses. In addition, for several sessions one or more specific variables could not be coded because of video recording problems because the mother predominantly used a non-English language. Therefore, the number of participants whose complete data were analyzed was 35 at 4 months, 38 at 6 months, and 39 at 9 months.

Procedure and coding

During each session, infants were seated in a modified walker with a tray, and mothers were seated on a pillow facing the infant (Figure 1). This arrangement controlled for differences in postural stability, distance between the participants, and the angle between the infant and mother. In this position, mothers could keep their infant's face and hands within their visual field when facing forward. Three cameras mounted on tripods recorded the interaction from different angles: one was centered on the infant's head and upper body, one on the mother's face and upper body, and one was further away, positioned lateral to the dyad, and zoomed out to capture both participants and their nearby environment. Videos were digitized and synchronized post-production, to facilitate coding (described in the following section).

At each session, the dyad interacted with three novel toys (mothers verified the novelty of all toys before the first session). The toys were the same for all participants, but different at each month. The toys were: a box with buttons, a caterpillar with rings, and a wobbling wolf doll at 4 months; a plush soccer ball, a light-up ring-shaped toy, and a wobbling chicken doll at 6 months; and a plush football, a light-up rattle, and a wobbling doll at 9 months. At the start of the session, two toys were placed in wells at the sides of the walker tray. Mothers were instructed to "play as they normally would" with their infants, but to try to leave one toy on the tray at a time and return the others to the wells (this was intended to

Figure 1. Example of frames from three video angles taken from home session at six months. Objects can be seen on tray and in wells on sides of tray. Because observations were recorded in participants' homes, sessions vary in background visual scene characteristics.

facilitate coding); however, toys in the wells were visible to infants and within their reach, and infants could (and did) freely retrieve toys from the wells. Additionally, to address another question, mothers were instructed to occasionally draw infants' attention to two targets located out of reach in specific locations; thus, mothers freely chose times (at least once per target) to punctuate the object-play interaction with a brief bid to re-direct the infant's attention. This activity was designed to represent the common situation of a caregiver interrupting an interaction to call an infant's attention to something. Mothers spent an average of 8% of the interaction time engaged in this secondary attention-directing task. Excluding those intervals had no significant effect on our results; therefore, here we report analyses of the entire session including the attention-directing intervals. The first three minutes of each session were analyzed because most sessions included at least three minutes of interaction during which the infant remained attentive. Mean session duration was 171.8 seconds at 4 months, 178.8 seconds at 6 months, and 177.0 seconds at 9 months.

We have previously reported data on changes in infant and mother gaze patterns and hand-object contact in a subsample of 26 mother–infant dyads (randomly selected) from this dataset (de Barbaro et al., 2015). For the current study, we expanded this dataset to include the entire sample (42 dyads). Additionally, for all dyads we coded all utterances, defined as bouts of meaningful speech separated by nonvocalizing periods of ≥200 ms. Nonlinguistic maternal vocalizations (e.g., sound effects, gasps, emotive sounds, etc.) were not included in the current analyses. Utterances were additionally classified as naming (i.e., containing a conventional label for one of the toys) or non-naming. In addition, we coded infant prelinguistic vocalizations, excluding cries, grunts, burps, and other organic sounds. For all dimensions coded, coders (blind to specific hypotheses) annotated the videos frame-by-frame at 10 Hz. The set of behaviors coded and reported here is detailed in Table 1. Figure 2 shows a sample time series of data from one session.

Table 1. Behavioral coding scheme.

Behavior	Definition
Infant Gaze	Target: one or more of the toys, or mother's face, or other (any location except one of the toys or the mother's face, e.g., the tray, walls, furniture, or extraneous objects)
Mother Gaze	Target: one or more of the toys, or infant's face, or other (any location except one of the toys or the infant's face, e.g., the tray, walls, furniture, or extraneous objects)
Infant Hands	Empty, or contacting one or more of the toys (ignoring gaps in contact of < 2 s). Mouthing the toys was also included, but was almost exclusively accompanied by handling.
Mother Hands	Empty, or contacting one or more of the toys (ignoring gaps in contact of < 2 s)
Infant Vocalization	Any vocal sound, excluding cries, grunts, burps, and other organic sounds
Mother Speech	All verbalizations, excluding sound effects and other non-linguistic vocalizations. Utterances are defined as bouts of speech separated by ≥ 200 ms of silence. Each utterance was further categorized as naming (e.g., "*You got the ball*") or nonnaming (e.g. *"What is that?"*).

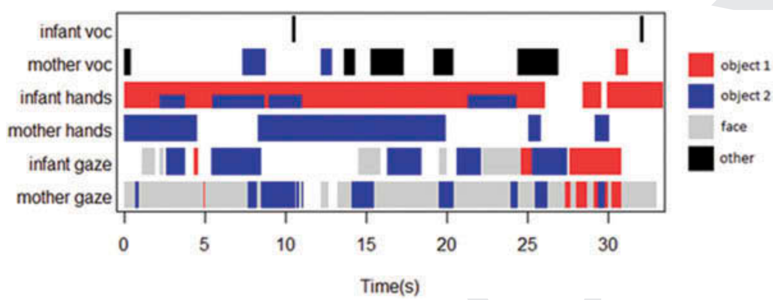

Figure 2. Example time series of data from part of one session. First row: Bars represent times when the infant vocalized. Second row: Bars represent times when the mother was speaking, and colors indicate naming utterances for the respective objects. Remaining rows: Colored bars represent times when the modality was directed to a specific target (objects or partner's face). Portions of bars split into two colors represent periods of simultaneous contact with multiple objects.

For reliability purposes, a second coder independently annotated infant gaze in 37% of the entire sample, mother gaze in 22%, infant hands in 33%, and mother hands in 37% of the sample (reliability samples were quasi-randomly chosen and age-stratified). Reliability was calculated separately for each variable. Inter-coder agreement was 83% for infant gaze, 85% for mother gaze, 89% for infant hands, and 95% for mother hands. Cohen's kappa (Cohen, 1968) was .79 for infant gaze, .78 for mother gaze, .85 for infant hands, and .92 for mother hands. A second coder also independently transcribed maternal speech and infant vocalizations for 30 sessions. Agreement for the timing of vocalization onsets was calculated as the average proportion of all vocal events with onsets matching within 200 ms. Agreement averaged 90% for mother utterances and 68% for infant vocalizations.

Statistical analysis

Our analytic approach was as follows: We first report overall age-related trends in behavior. Next, we describe contingencies between infant actions and mother speech. Next, we present the detailed time course of dyadic gaze and hand activity preceding and following naming utterances.

Repeated measures ANOVAs (rmANOVA) were used to test for age-related trends in the overall rates of all maternal utterances, maternal naming utterances, infants' and mothers' gaze to objects, and infants' and mothers' handling of objects. Conditional probability models were then used to examine rates of maternal utterances—all utterances, and specifically naming utterances—as a function of infants' gaze, manual behaviors, and vocalizations. Separate probability models were computed for all utterances and naming-utterances, relative to each type of infant behavior. Infant behaviors included the infants' gaze target, and each possible shift in gaze targets (seven types: object to object, object to face, face to object, object to other, other to object, face to other, or other to face); infants' object handling (i.e., number of objects handled: zero, one, or multiple), and each possible shift in object-handling (five types: zero to one, one to zero, one to multiple, multiple to one, and one to one). To model contingencies to gaze and object handling shifts, we compared the rate of utterances within 2 seconds after the shift to the rate over all other times.[1] Contingencies to infant gaze targets and object handling states were modeled directly using the rates of utterances at times infants were in each state.

Models were estimated using mixed-effects Poisson regression. This procedure tests for differences in the rates of a random point event (e.g., utterance onsets) across defined periods of time (infants' behavior states). It is a suitable analytic approach because other measures (e.g., proportion of actions that elicit a response) are sensitive to differences in base rate, and because the relative rate statistic can be interpreted as the magnitude of the signal available to the infant (Coxe, West, & Aiken, 2009). Models included age as a within-subjects continuous predictor, subject identity as a random effect, and infant behavior states (e.g., gaze at mother's face vs. objects vs. other) as a within-subjects factor. Age and subject identity were included in the models to control for individual and age differences in the base rate of maternal speech; however, for conciseness, only the effect of the infant behavior variable is reported. Whenever this effect was significant, we also report a model that includes the infant behavior X age interaction term, to show whether the contingency differed in strength with age.

Because we found a significant, novel effect in which infants' object-handling shifts from one to multiple objects (or vice versa) predicted mothers' naming utterances, we further investigated those shifts using rmANOVA to test for age-related changes in frequency, as well as session-wise correlations between the frequency of such shifts and mothers' naming rates.

We then characterized the time course of infants' and mothers' allocation of visual and manual attention to named objects before and after naming utterances. At each age, we computed the probabilities that each of these four modalities was engaged with the named object at different times relative to naming utterances. For each modality, all naming events were aligned (i.e., utterance onset time = 0) and, for every 0.1 second time step (between −10.0 and +10.0 sec), the proportion of events during which that modality (i.e., gaze or hands of mother or infant) was focused on the named object was calculated. Each modality is thereby represented as a time series of proportions (i.e., that the modality was focused on the named object at given time step over a window of ± 10 sec from naming utterance onset). Infant gaze and hands time-series are shown in Figure 3, and mother gaze and hands time-series are shown in Figure 4. At each time step, the probability of modality-engagement was compared to a baseline defined as the proportion of the entire session during which that modality was engaged with the object. The *p*-values of *t*-tests were thresholded at $p = .05$.

Results

Descriptive statistics

The average rates per minute of all maternal utterances, and of naming utterances specifically, at each age, are presented in Table 2.First mention of Table 2. rmANOVAs with age as a within-subjects factor revealed significant effects of age on rate of total utterances, $F(2,67) = 3.59$, $p < .05$, and on rate of naming utterances, $F(2,67) = 11.31$, $p < .001$. Post hoc tests comparing the 4 and 6 month sessions and the 6 and 9 month sessions were computed, using critical $p = .025$ to correct for multiple comparisons. These showed that rate of total utterances decreased from 6 to 9 months, $t(35) = -2.94$, $p < .01$, but the rate of naming utterances *increased* marginally from 4 to 6 months, $t(32) = 2.13$, $p < .05$, and significantly from 6 to 9 months, $t(35) = 2.82$, $p < .01$.

[1]The 2 sec window was chosen based on previous reported results showing that a 3-second window is optimal for detecting contingencies between infant actions and caregiver responses (Van Egeren, Barratt, & Roach, 2001); however, because we are considering more fine-grained and frequent behaviors (e.g., gaze shifts), we adopted a shorter window to minimize spurious contingencies. Nevertheless, to ensure that the results do not depend narrowly on our use of the 2-second criterion, we repeated all analyses with 1.5-and 2.5-second windows. The results using those windows were all qualitatively similar to those reported in the text. Contingencies to infant gaze targets and object handling states were modeled directly using the rates of utterances at times infants were in each state.

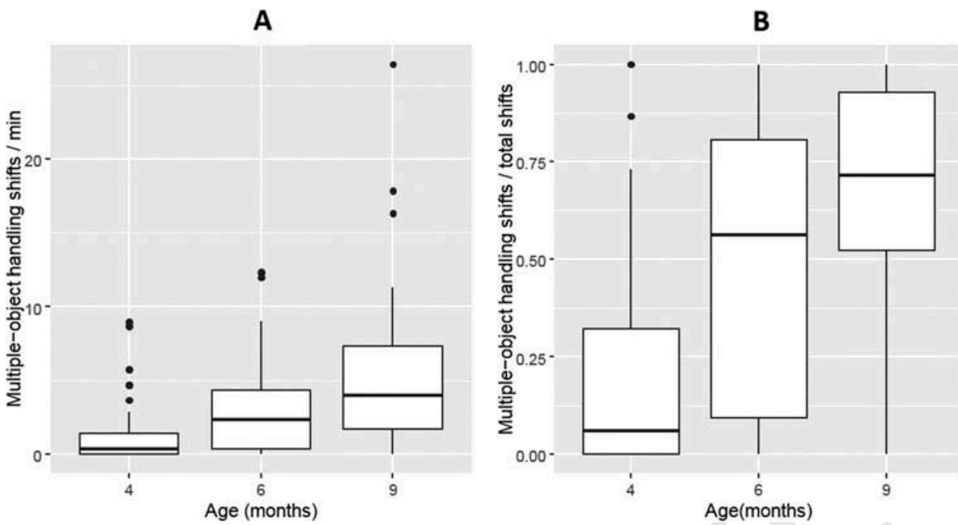

Figure 3. Infant behavior around naming utterances at each month. Lines represent average proportions of instances in which, at that time, infants' hands or gaze were focused on the target object, time-locked to onsets of naming utterances. Shaded regions represent the standard error of the mean. Bars at the top of graphs represent times when the naming-association index was greater than chance at $p < .05$.

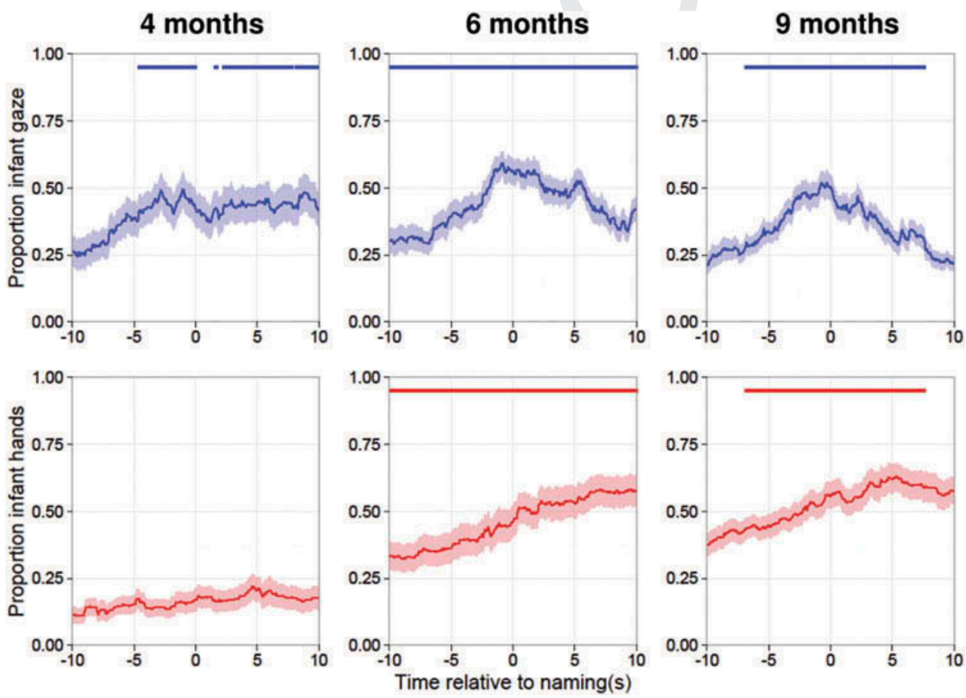

Figure 4. Mother behavior around naming utterances at each month. Lines represent average proportions of instances in which, at that time, mothers' hands or gaze were focused on the target object, time-locked to onsets of her naming utterances. Shaded regions represent the standard error of the mean. Bars at the top of graphs represent times when the naming-association index was greater than chance at $p < .05$.

Table 2. Average number of naming and total utterances per minute at each month. *SD* in parentheses.

	Total utterances/min	Naming utterances/min
4 months	20.5 (4.6)	1.5 (1.5)
6 months	21.5 (5.3)	2.3 (1.4)
9 months	19.1 (4.9) *	3.1 (1.9) *

Note. * denotes significant change from previous month, $p < .025$.

Table 3. Mean proportion of time infants or mothers were looking at, or handling, at least one object.

	Infant gaze	Infant hands	Mother gaze	Mother hands
4 months	.73 (.13)	.43 (.29)	.36 (.12)	.68 (.19)
6 months	.65 (.12) *	.74 (.25) *	.39 (.11)	.47 (.18) *
9 months	.54 (.15) *	.83 (.20)	.39 (.12)	.39 (.18) *

Note. SD in parentheses. *denotes significant change from previous month, $p < .025$.

Table 3. shows the mean proportions of time that the mother or infant, respectively, either looked at or handled at least one object, at each age. These analyses replicate our previous findings (de Barbaro et al., 2015) in the current larger dataset. Specifically, rmANOVAs with age as a within-subjects factor revealed a significant effect of age on prevalence of infant gaze, infant handling, and mother handling (*ps* < .001), but not on mother gaze, $p = .39$. Post hoc tests showed that infant gaze to objects decreased from 4 to 6 months, $t(40) = -3.11$, $p < .005$, and from 6 to 9 months, $t(40) = -4.82$, $p < .001$. Infant object handling increased from 4 to 6 months, $t(40) = 7.21$, $p < .001$, and showed an increasing trend from 6 to 9 months, $t(41) = 1.84$, $p = .07$. Mothers' object handling decreased from 4 to 6 months, $t(38) = -6.20$, $p < .001$, and from 6 to 9 months, $t(41) = -2.87$, $p < .01$.

Verbal responses to infants' gaze

We investigated maternal responsiveness to infant gaze patterns by testing whether mothers' utterance rate or naming rate differed as a function of either infants' current gaze target or recent changes in infants' gaze target. Infants' gaze target was classified as one of three types: Face, Object, or Other. Rates of maternal speech contingent on infants' gaze target are shown in Table 4. Mothers produced fewer total utterances when the infant looked at objects ($p < .001$) and more utterances when the infant looked at her face ($p < .001$), relative to infants' looks at other locations. In contrast, mothers produced more naming utterances when the infant looked either at objects ($p < .001$) or at her face ($p < .01$). Thus, when infants looked at their mother's face, mothers talked more overall, but when infants looked at objects, mothers named objects more and talked less overall.

Next we examined whether maternal utterance rates were contingently related to any of seven types of infant gaze shifts: object-to-other, other-to-object, object-to-face, face-to-object, face-to-other, other-to-face, and object-to-object. Applying a Bonferroni correction to each set of seven tests, the significance level was set at $p = .007$.

The results, summarized in Table 5, are generally consistent with the analyses of gaze targets. Mothers' total utterances were significantly more frequent after infants' gaze shifts from objects to face, other to face, and face to other (*ps* < .001). Naming utterances were significantly more frequent after infants' shifts from face to objects ($p < .005$) and from other to objects ($p < .005$).

Table 4. Poisson regressions for the contingencies between infant gaze targets and mothers' utterances.

	Total Utterances			Naming Utterances		
Gaze Target	Relative Rate	β	*p*	Relative Rate	β	*p*
Object vs. None	0.87 *	−.144	< .001	1.91 *	.646	< .001
Face vs. None	1.18 *	.164	< .001	1.46 *	.380	< .010

Note. Exponentiated coefficients are reported, which are interpreted as the ratio of the rate of responses between the two infant gaze targets. * $p < 0.5$.

Table 5. Poisson regressions for the contingencies between infant actions and mothers' utterances.

	Total Utterances			Naming Utterances		
Infant Behavior	Relative Rate	β	*p*	Relative Rate	β	*p*
Gaze: Object → Other	1.01	.008	.800	1.23	.208	< .05
Gaze: Other → Object	1.00	.000	.990	1.29 *	.260	< .005
Gaze: Object → Face	1.19 *	.176	<.001	1.21	.194	.200
Gaze: Face → Object	1.05	.047	.370	1.49 *	.399	< .005
Gaze: Face → Other	1.14 *	.131	< .001	0.50 *	−.681	< .001
Gaze: Other → Face	1.34 *	.294	< .001	1.03	.034	.810
Gaze: Object → Object	0.99	−.014	.780	1.14	.132	.340
Hand: None → One	0.90	−.104	.110	1.23	.211	.230
Hand: One → None	1.07	.070	.230	0.91	−.084	.670
Hand: One → Multiple	0.94	−.061	.560	1.43 *	.361	< .010
Hand: Multiple → One	0.99	.006	.930	1.47 *	.385	< .010
Hand: Object → Object	0.97	−.032	.740	1.34	.294	.190
Infant Vocalization	1.18 *	.163	< .010	1.10	.174	.580

Note. For each infant behavior, we compared maternal verbalizations in the 2 s after each infant behavior with other periods. The regression models test differences in rates of maternal response between these two types of intervals. Exponentiated coefficients are reported, which are interpreted as the ratio of the rate of responses between the two types of periods. * adjusted $p < 0.05$.

To test whether contingencies between infant gaze and maternal speech changed as a function of infant age, we repeated the regressions that showed significant effects, with the addition of age X infant gaze interaction terms. The interaction was not significant in any case except for a positive interaction between age and gaze to objects on naming utterances, $\beta = .147$, $p < .005$. That is, as infants got older, mothers responded more contingently to infants' object-gaze by naming objects.

Vocal responses to infants' hand activity

We investigated maternal responsiveness to infants' hand activity by testing whether mothers' utterance rate or naming rate differed as a function of either infants' number of objects handled or recent changes in object handling. Infants' object handling was divided into times when infants handled no object, one object, or multiple objects. No significant relations were found between number of objects handled, and either naming or total utterances (Table 6).

Next we examined whether maternal utterance rates were contingently related to any of five types of shifts in infants' object handling: from no object to one object, one object to no object, one object to multiple objects, multiple objects to one object, or one object to another object.

Applying a Bonferroni correction to each set of 5 tests, the critical significance level was set at $p = .01$. Results are summarized in Table 5. Mothers' total utterances were not significantly contingent on object-handling shifts. However, naming utterances were significantly contingent on two shift types: from one object to multiple objects and multiple objects to one object (*p*s < .01).

To test whether maternal contingent vocal responsiveness to infant hand actions changed as a function of the infant's age, we repeated the regressions that showed significant effects, adding age X infant behavior interaction terms. None of the interaction terms reached significance (*p*s > .2). Therefore, maternal vocal responsiveness to infants' manual shifts did not change with age, although the low frequency of shifts involving multiple objects at 4 months limited our ability to detect an age interaction.

Table 6. Poisson regressions for the contingencies between infant hand states and mothers' utterances

	Total Utterances			Naming Utterances		
Objects held	Relative Rate	β	*p*	Relative Rate	β	*p*
One vs. None	1.02	.022	.46	1.01	.009	.92
Multiple vs. None	1.00	−.004	.93	1.04	.044	.76

Note. Exponentiated coefficients are reported, which are interpreted as the ratio of the rate of responses between the two types of periods. $^{*}p < 0.05$.

Vocal responses to infant vocalizations

We investigated maternal responsiveness to infants' prelinguistic vocalizations by testing whether mothers' utterance rate or naming rate were predicted by infants' vocalizations (Table 5). The 2-second window defining contingent responses started at the offset of infant vocalizations rather than the onset because vocal turn-taking tends to avoid overlap (Sacks, Schegloff, & Jefferson, 1974). As expected, mothers' total utterances were significantly contingent on infant vocalizations ($p < .01$). However, naming utterances were not contingently related to infant vocalizations ($p = .58$).

Relations between multiple-object handling and naming utterances

The foregoing analyses confirmed our prediction that mothers' speech is contingent on their infant's manual activity. Specifically, naming utterances were predicted by infants' shifts from handling one object to multiple objects or vice versa. In addition, naming utterances increased in overall frequency as infants aged. Previous work in our lab indicates that infants increasingly manipulate multiple objects simultaneously from 4 to 6 months and from 6 to 9 months (de Barbaro et al., 2015). This suggests a potential developmental pathway whereby changes in the language infants hear—specifically naming—are mediated by developmental changes in their manual activity. To evaluate whether that pathway is consistent with our current results, we first investigated whether infants' multiple-object handling shifts indeed increased with age. Second, we investigated whether, at each age, those shifts correlate with the overall rate of naming utterances.

The rmANOVAs with age as a within-subjects factor revealed that infants' multiple-object handling shifts increased with age, both as a rate per minute, $F(2,80) = 11.9$, $p < .001$, and as a proportion of handling shifts, $F(2, 76) = 27.1$, $p < .001$ (Figure 5). Post hoc tests showed that the rate of multiple-object handling shifts increased significantly from 4 to 6 months, $t(40) = 3.22$, $p < .005$, and marginally from 6 to 9 months, $t(41) = 2.21$, $p < .05$. Similarly, the proportion of handling shifts that involved multiple objects increased from 4 to 6 months, $t(39) = 4.62$, $p < .001$, and from 6 to 9 months, $t(40) = 3.23$, $p < .005$. The partial correlation between infants' multiple-object handling shifts and mothers' rate of total and naming utterances, controlling for the infant's age in days, was calculated at each month (**Table 7.**). Applying a Bonferroni correction to each group of 3 tests (across ages), the significance level was set at $p = .017$. As expected, infants' rates of multiple-object handling shifts were not significantly related to mothers' total utterances ($ps > .06$). However, multiple-object shifts were significantly positively correlated with mothers' rate of naming utterances at 4 months ($p = .01$) and at 6 months ($p = .01$), though not at 9 months ($p > .3$). This pattern is consistent with the hypothesis that developmental changes in infants' manual coordination influence not only the timing but also the content of mothers' speech: not only did infants' multiple-object handling shifts increase with age in parallel with mothers' increasing rate of naming, but in addition, at 4 and 6 months individual differences in multiple-object handling predicted mothers' rate of object naming.

Time course of activity before and after naming utterances

We next described the time course of infants' and mothers' allocation of visual and manual attention to named objects before and after naming utterances, computing, for each of four modalities (infant gaze, infant hands, mother gaze, mother hands), time series of proportions representing the probability that the modality was engaged with the named object at each time relative to the onset of a naming utterance. Infant gaze and hands time-series are shown in Figure 3, and mother gaze and hands time-series are shown in Figure 4. At each time step, we tested whether each modality was engaged with the named object significantly more than a baseline defined as the proportion of the entire session during which that modality was engaged with the object.

At 4 months, infants frequently directed gaze to the named object briefly before naming, and for a more prolonged period after naming, whereas their hands were not differentially directed to the named

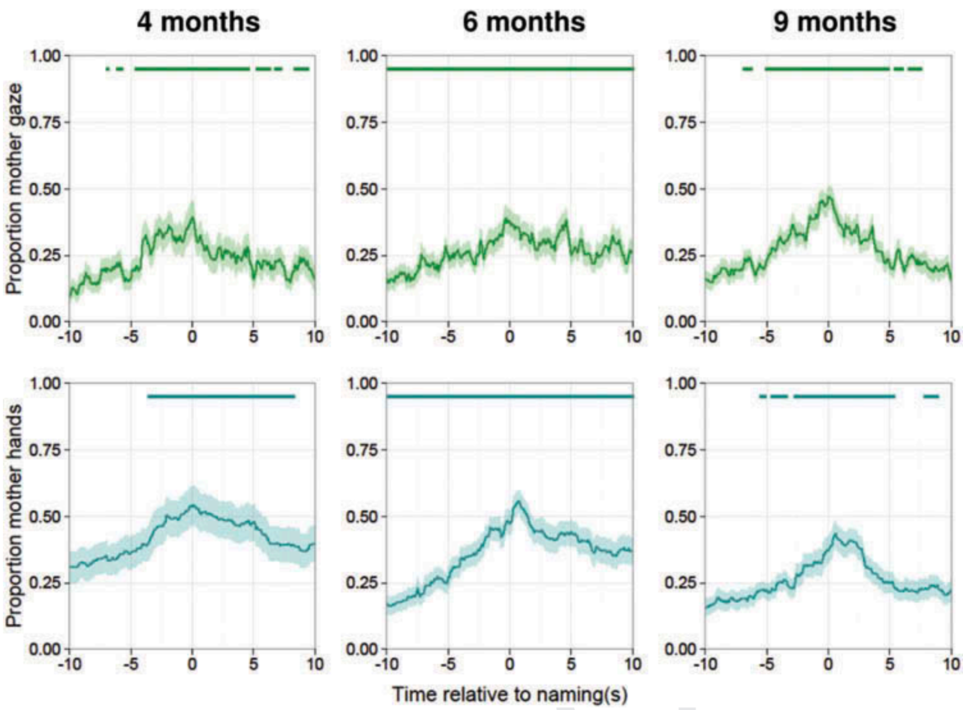

Figure 5. Increase in multiple-object handling shifts with age. A: multiple-object handling shifts per minute at each age. B: multiple-object handling shifts as a proportion of total shifts at each age.

Table 7. Partial correlations between rate of infants' multiple-object handling shifts and maternal speech rates, controlling for infant's age in days

Age	Utterances/min	Labels/min
4 months	−.03	.42*
6 months	−.01	.40*
9 months	−.30	−.15

Note. **p* < .017.

object around naming. At 6 months, both gaze and hands were significantly more often directed to the object for the entire window. However, the shape of the temporal profile changed from 4 to 6 months in that at 6 months, infant gaze peaked around the time of naming, and handling was more frequent after naming than before. At 9 months, the shapes of the temporal profiles were similar to those at 6 months, but infants' gaze and hands were significantly directed to the named object during a more precise window of time relative to naming.

Mothers' gaze and object handling around naming utterances also changed with infant age. Notably, at 6 months, associations between naming and both maternal modalities also robustly exceeded chance across the entire 20 s window, whereas the associations were more temporally precise at 9 months. Because mothers' visuomotor skills presumably did not change, this suggests that mothers adapted their sensorimotor patterns to infants' increasingly fluid exploration. However, the temporal profile of mothers' handling of named objects differed from that of infants. Specifically, at all ages, mothers' handling peaked in synchrony with naming onset, whereas infants, with age, increasingly handled the named object *after* naming onset.

Discussion

Although recent research demonstrates the importance of contingency detection in infant learning, we are only beginning to understand how structured social contingencies change during the first year and contribute to infants' experience with language, people, and objects. We examined relations between occurrences of mothers' speech acts, and object-naming utterances in particular, and infants' and mothers' looking and object-handling actions. The results reveal regularities in the patterning of speech and exploratory actions that could support infants' word learning across the first year. Mothers' speech was contingent on infants' gaze, manual actions, and vocalizations. These contingencies are potential cues that could help infants learn not only specific object names, but also how their own actions influence caregivers' speech. In addition, contingencies were specific to speech content and changed with age as infants produced different sets of actions.

Some contingencies involve simply infant's visual attention: mothers were more likely to speak when their infant looked at them, and less likely to speak when their infant looked at objects. This pattern is consistent with Lloyd and Masur's (2014) report that mothers responded less to 13-month-olds' object initiatives than social initiatives. Notably, there is evidence that contingencies between infant gaze and maternal speech emerge quite early: Lavelli and Fogel (2005) found that mothers spoke more to infants as young as 1 month when their infant was looking at them, although the effect became stronger by 3 months, when infants' social gaze is more expressive and differentiated (see also Henning, Striano, & Lieven, 2005). The current data did not reveal change in mothers' contingent responses to their infant looking at them, suggesting that the contingency is well established by 4 months.

The results also indicate that the content of maternal speech is related to the infant's gaze. In particular, mothers' naming utterances were contingent on infants looking at the mother's face, or shifting gaze to objects. As infants got older, the timing of mothers' naming utterances became more tightly contingent on infants' gaze to objects. These results are consistent with previous reports: Penman, Cross, Milgrom-Friedman, and Meares (1983) found higher proportions of maternal speech about external referents when infants looked at objects at 3 and 6 months, and at 4 months, joint attention predicts lexical content in maternal vocalizations (Brousseau, Malcuit, Pomerleau, & Feider, 1996). In a cross-cultural study of American and Japanese 3-month olds, the distribution of speech act types and referents differed based on infants' gaze targets, although the specific contingencies differed between cultures (Morikawa, Shand, & Kosawa, 1988). The current study thus confirms that mothers adapt their distribution of functional utterance types in response to infants' gaze and extends that evidence to object-naming utterances.

Maternal speech was also contingent on infants' manual activity. Although total speech rate did not differ in response to infants' object handling, mothers' production of object-naming utterances was contingent on infants' shifts from handling one object to multiple objects, and from multiple objects to one object. Because we were interested in the effect of developmental changes in infants' manual activity on their contingent caregiver speech, we further investigated age-related changes in infants' shifts in handling multiple objects. From 4 to 9 months, infants increased their object-handling shifts involving multiple objects, both per minute and as a proportion of total object-handling shifts. 4- and 6-month-olds who produced more multiple-object shifts heard more object-naming utterances. By 9 months, when most infants can effectively manipulate multiple objects, there were no significant individual differences in mothers' object naming, although the moment-to-moment contingencies between infants' multiple-object shifts and maternal speech remained robust. Thus, changes in infants' motor coordination are related to increased exposure to naming utterances.

These results build on those of de Barbaro et al. (2015), who described nonverbal dynamics of object play in a randomly selected subset of the sessions reported in the current study. Those results suggest that development of infants' ability to distribute their attention during play, as reflected by infants' "decoupling" of gaze and hands (i.e., looking at one object while handling another, or handling multiple objects simultaneously), has implications for social interactions. Notably, decoupling is linked to emerging social behaviors such as turn-taking and imitation (de Barbaro et al., 2013). The current results suggest that increased object naming might represent another aspect of social routine maturation accompanies infants' advances in object exploration and attention. One possible interpretation is that changes in maternal speech occur because infants produce more of the actions that tend to elicit object naming. However, it is also possible that infants' advances in object handling influence maternal speech by changing mothers' perceptions of their infants. Mothers' perceptions of their 4- and 8-month-old infants' intentionality correlate positively with mothers' sensitive interaction style (Feldman & Reznick, 1996), and between 10 and 13 months, parents' perception of their infant as an individual positively predicted receptive vocabulary (Walle, 2016). Future research could therefore investigate the relationship between infants' object-handling development and caregivers' perceptions of their cognitive maturity.

Why might mothers disproportionately name objects when infants pick up or put down a second object? One possibility is that at these moments mothers simply perceive infants to be more attentive to the objects. However, it is also possible that these handling-switches are adaptive times for object naming because they highlight contrasts between objects. At these times infants are likely focusing attention on one object, but the other is still available and represented in working memory. Object names in utterances that occur at those times can be associated with features that distinguish the new focal object from the previous one. To clarify whether mothers used object-handling shifts specifically to highlight the *new* object, we computed the proportion of naming utterances contingent on one-to-multiple shifts that named each of the two objects. Out of these, 58% named the newly handled object, whereas 32% named the previously handled (or "given") object that was already handled before the shift. Highlighting new objects around shifts is consistent with evidence that *comparisons* facilitate children's learning of words and categories (Gentner, Loewenstein, & Hung, 2007; Gentner & Namy, 1999). By producing naming utterances when infants start or stop handling multiple objects, rather than during prolonged episodes of handling one or more objects, mothers increase the probability that the object label will be associated with contrastive features of one object versus the other, rather than irrelevant properties such as an object's location or motion. If caregivers regularly distribute naming utterances in such informative ways, it might not only help infants build associations between object labels and referents, but also guide their inferences about which object features to assign to nouns, which are otherwise highly indeterminate (Quine, 1960).

Mothers' utterances were also more frequent following infants' vocalizations. There is ample evidence that mothers spontaneously impose turn-taking rhythm in vocal response to infants' preverbal vocalizations (e.g., Papoušek & Papoušek, 1989). Such adult-imposed contingent input ostensibly socializes infants for discourse conventions that show culturally predictable temporal parameters (Stivers et al., 2009). Accordingly, by 4 months infants actively participate in vocal turn-taking (Stevenson, Ver Hoeve, Roach, & Leavitt, 1986). Notably, however, we found that infant vocalizations predicted mothers' utterances in general, but not naming utterances in particular. This suggests that contingencies between infant behaviors and maternal speech have differentiated functions: some might highlight the responsive nature of verbal interactions in general, whereas others might help infants associate maternal speech types or specific words with external referents.

We also observed different time courses of infants' and mothers' gaze and hand engagement with named objects, relative to the onset of naming utterances. At all ages, mothers' gaze and hand engagement both tended to peak around the onset of naming. The time course of infants' gaze and hand engagement relative to naming, however, showed a more complex developmental trajectory. Infants tended to look at the named object at all ages, but as they got older their looks peaked closer to the onset of naming. Infants handled named objects more by 6 months, and their handling increased after the onset of naming utterances. This increase suggests either that mothers name objects in anticipation of infants' activity, or that infants use mothers' naming utterances as a cue to sustain attention to objects. The latter possibility would create a positive feedback loop that might help infants maintain joint attention with caregivers; however, controlled experiments are necessary to determine whether caregiver speech affects infants' subsequent attention in naturalistic contexts. Similar to the present results, Yu and Smith (2012) found that older (18-month-old) infants held named objects more than did parents after naming events; however, in that study, infants' object holding peaked at the time of naming, while in the present study parents' infants' object holding peaked later. Nonetheless, the time courses of modalities in both studies indicate that object naming does not simply overlap with infants' object gaze and handling, but is embedded in temporally structured sequences of co-exploration of potential referents. Often, for example, infants watched as their mother held, looked at, and named an object, and then retrieved the object themselves. Consistency in these sequences might help infants associate naming utterances with patterns of sensorimotor experience in order to ground the possible meanings of object names within those utterances.

Underlying the process of learning words, infants' multimodal experiences may contribute to the formation of neural networks that process language jointly with ongoing manual action. In adults, inferior frontal cortex is activated in language production as well as action production and recognition tasks (Hamzei et al., 2003). Language processing networks also integrate speech with manual activity in the form of co-speech gesture. In fMRI experiments, inferior frontal gyrus (Broca's area) showed greater metabolic response when co-speech gesture conveyed additional information than when it reiterated information present in speech (Dick, Mok, Beharelle, Goldin-Meadow, & Small, 2014). Co-speech gesture also elicited a stronger response than speech without gesture in cortical regions associated with language comprehension, both in adults (Dick, Goldin-Meadow, Hasson, Skipper, & Small, 2009) and in children aged 8–11 years (Dick, Goldin-Meadow, Solodkin, & Small, 2012).

Relatedly, a form of multimodal experience with language and manual activity also seems to influence mothers' integration of speech and manual sensorimotor activity. Mothers showed differential N1 and P2 ERP components (relating to selective attention and discrimination) following mismatches between tactile cues and tactile-related words, whereas nonmothers did not show such responses, presumably because tactile-lexical associations were more salient to mothers, who spend more time explicating such associations with infants and toddlers (Tanaka, Fukushima, Okanoya, & Myowa-Yamakoshi, 2014). Thus, mothers' cortical networks might develop speech-action integration in an activity-dependent manner. We speculate that a similar process may occur in infants as a result of experience with associations between speech and motor and/or haptic experience.

Although it is difficult to determine whether changes in integration of sensorimotor and speech processing in infants are a result of experience or maturation, at least one study (Imada et al., 2006) shows that such integration does develop during the first year. Neonates showed MEG responses to speech sounds only in temporal auditory areas, but at 6 and 12 months activation was observed in both temporal areas and inferior frontal gyrus (Imada et al., 2006). However, it is not known whether such early-developing cross-modal processing is limited to direct, temporally precise links such as those between mouth movements and speech sounds, or whether it also encompasses less deterministic associations such as the social contingencies we observed.

Word-referent associative learning is unlikely to account for the entirety of early lexical development (Waxman & Gelman, 2009). Nevertheless, contingencies between infant actions and maternal speech suggest that associative learning plays a broader role in language acquisition. One way action contingencies could facilitate learning is if infants associate their own actions with expectations of informative input from caregivers. For example, Rochat, Querido, and Striano (1999) found that from 2 to 6 months infants learn to expect a turn-taking action pattern during "peek-a-boo" games–including the expectation that the infant's own action will elicit a particular kind of response, within a certain interval, from the adult. This illustrates that infants can learn to anticipate that their own actions will elicit specific communicative acts from adults. These expectations can then cue infants' attention in the service of word learning (Smith, Colunga, & Yoshida, 2010). Indeed, by 9 months, infants attend more to novel visual stimuli in the presence of novel words (Balaban & Waxman, 1997). Contingent responses to infants' self-generated actions are optimal for developing such expectations, both because infants seem predisposed to detect the causal force of their own actions (Bahrick & Watson, 1985; Bigelow, 1999; Watson, 1972), and because infants can generate the eliciting signal at times and contexts when they are receptive to input.

In addition to effects on word learning, social contingencies could potentially facilitate infants' understanding of others' attention or other mental states. Caregivers' responsiveness depends on their being attentive to the infant. Therefore, infants might become sensitized to caregivers' attention once they have detected the social contingencies that joint attention affords. If so, then participation in increasingly sophisticated social contingencies may form a foundation for infants to imbue their caregivers' attention and actions with meaning (Baldwin, 1991; Carpendale & Lewis, 2004, 2010; Rączczaszek-Leonardi, Nomikou, & Rohlfing, 2013; Reddy, 2001).

Taken together, our results underscore that no unitary construct such as "responsiveness" can precisely capture the various ways caregivers act contingently on infant behavior. Instead, dyadic multimodal speech-and-sensorimotor contingencies provide a rich source of event-sequential information for infants. That information is available to young infants, but it changes as infants mature and acquire new behavioral capacities. At each point in development, an infant's social environment emerges differently from the set of contingent responses that are active at that time.

The current data set has several limitations. The infant behaviors that appeared to generate contingent responses might be correlated with unobserved behaviors that mediate the mother's response. It is also likely that combinations of infant behaviors, such as object handling while vocalizing or looking at the caregiver's face, interact to elicit contingent responses that cannot be captured by independent contingencies to individual infant behaviors. However, the current dataset did not have enough statistical power to test for all possible interactive effects of multiple infant behaviors on maternal speech.

The current study involved observations of play in dyads in an urban, primarily English-speaking community in the United States. Practices of playing and speaking with infants vary widely across cultures and across contexts within a culture (e.g., Altınkamış, Kern, & Sofu, 2014; Bornstein, Toda, Azuma, Tamis-LeMonda, & Ogino, 1990). Therefore, the observed patterns cannot be assumed to generalize to other populations. However, in studies of early mother-infant interaction across several cultures, caregivers have been observed to respond contingently to infants' vocalizations, even in cultures with low overall levels of infant-directed speech and toy play (Bornstein, Putnick, Cote, Haynes, & Suwalsky, 2015; Kärtner et al., 2008). Thus, infants' self-generated activity might play a role in many cultures in driving the micro-behavioral structure of their language environment by shaping caregivers' infant-directed speech across the first year. However, it is likely that the specific behaviors that contribute to this structure differ somewhat from culture to culture; for example, Fogel, Toda, and Kawai (1988) found that whereas American mothers verbalized in response to their 3-month-olds' vocalizations and gaze, Japanese mothers responded with facial expressions rather than speech, and did not respond contingently to their infants' vocalizations.

The analyses presented in this paper are exploratory in nature and would benefit from confirmatory replication. Nevertheless, these results show that the occurrence and object-naming content of maternal speech are contingent on infants' gaze and hand actions, and that the precise pattern of contingencies, and of infants' object exploration, evolves from 4 to 9 months. Future research should investigate contingent responsiveness at a similar level of granularity in additional contexts and cultures, and measure both the theoretical learnability and infants' actual learning of the information made available in these social interactions.

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