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Sensorimotor Decoupling Contributes to Triadic Attention: A Longitudinal Investigation of Mother–Infant–Object Interactions

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Previous developmental accounts of joint object activity identify a qualitative "shift" around 9–12 months. In a longitudinal study of 26 dyads, videos of joint object interactions at 4, 6, 9, and 12 months were coded for all targets of gaze and manual activity (at 10 Hz). At 12 months, infants distribute their sensorimotor modalities between objects handled by the parent and others controlled by the infant. Analyses reveal novel trajectories in distributed joint object activity across the 1st year. At 4 months, infants predominantly look at and manipulate a single object, typically held by their mothers. Between 6 and 9 months, infants increasingly decouple their visual and haptic modalities and distribute their attention between objects held by their mothers and by themselves. These previously unreported developments in the distribution of multimodal object activity might "bridge the gap" to coordinated joint activity between 6 and 12 months.

Humans are differentiated from other species by our willingness to teach and learn from others (Tomasello, 1999; Vygotsky, 1978) and by our interest in and responsiveness to other individuals' activity. *Triadic engagement* refers to interactions between two partners who are mutually engaged with one another while sharing a focus of activity. In infant–parent interactions, these episodes provide opportunities for infants to access and participate in parents' skilled practices (Lave & Wenger, 1991). Studies indicate that triadic interactions support a wide range of developmental practices, including language learning (Bruner, 1975), social skills (Bornstein & Tamis LeMonda, 1989), object manipulation (Lockman & McHale, 1989; Zukow-Goldring & Arbib, 2007), and culture-specific routines (Bruner, 1987). This study investigated triadic activity by examining a common activity among infant–parent dyads: shared manipulation and exploration of objects. For simplicity, we shall refer to this as object play.

Object play can include a wide variety of particular actions, ranging from bouts of object examination and sharing/giving to imitation and "games" involving simple turn-taking routines or repetition of actions such as stacking and toppling blocks. However, the nature of object play interactions appears to develop considerably during the 1st year. Object play in the first 9 months has been described as dominated by dyadic interactions, wherein infants actively engage with either a social partner or an object, but do not smoothly coordinate their attention and activities between partners and objects (Adamson & Bakeman, 1991). These early interactions are sometimes described as asymmetrical (Hsu & Fogel, 2003; Messer & Vietze, 1984).

It is often claimed that in very early object interactions, parents actively initiate object selection and activities, and infant passively observe (Bakeman & Adamson, 1984). Between 4 and 6 months, however, as infants begin to reach for and manipulate objects, this asymmetry reverses, and infants are said to more actively initiate engagement with objects, whereas parents increasingly observe and follow the infant's lead (Bruner & Watson, 1983; Lamb, Morrison, & Malkin, 1987). However, it is commonly believed that up to 6 more months will pass before parents and infants engage in symmetric or coordinated triadic activities (Adamson & Bakeman, 1991), such as games and routines. Adamson and Bakeman (1991, p. 21) refer to this interval between infant-driven object engagement and triadic activities as a "curious developmental gap." That is, if infants engage with social partners around 3 months (Brazelton, Koslowski, & Main, 1974; Kaye & Fogel, 1980; Stern, 1974) and with objects around 4–6 months (Bruner & Watson,

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1983; Lockman & McHale, 1989), it is unclear why triadic engagement does not emerge until 9–12 months (Adamson & Bakeman, 1991; Carpenter, Nagell, & Tomasello, 1998).

We investigated this "curious gap" by documenting detailed behavioral changes between 4 and 12 months of age. One possibility is that there is continuity of development from dyadic to triadic interaction, and the "gap" or latency period might simply be an artifact of the measures used to assess interactions in previous studies. In those studies, interactions were typically characterized by global qualitative categories of joint object activity (e.g., passive vs. active vs. coordinated), and were sparsely coded (e.g., every 1–3 s; Bakeman & Adamson, 1984; Hsu & Fogel, 2003). Global categories allow for flexibility in classifying dyadic activities. However, differences in the timing of gaze and manual activity are nevertheless critical for making these distinctions. For example, as defined by Bakeman and Adamson (1984), passive and active states appear to be mainly differentiated by the presence of infant manual object contact, while coordinated joint attentional states additionally include gaze contact with the partner as well as the object. Although such global coding schemes can identify gross shifts in dyadic engagement, they obscure the fine-grained changes in timing and coordination of multimodal sensorimotor activity that eventually yield triadic engagement. Drawing on research that considers social interaction as a distributed and dynamic system (e.g., Fogel & Thelen, 1987; Forster, 2002; Forster & Rodriguez, 2006; Hutchins, 1995; Jaffe, Beebe, Feldstein, Crown, & Jasnow, 2001; Johnson, 2001, 2010; Oyama, 1985/2000; Ruesch & Bateson, 1951; Stern, 1971; Thelen & Smith, 1994; Vygotsky, 1978), our approach simultaneously tracks patterns of dyadic coordination as well as the microdynamics of mother and infant multimodal activity by which these dyadic states are achieved (see de Barbaro, Johnson, Forster, & Deák, 2013). This allows us to describe how dyadic and triadic interactions emerge from characteristic sequences of gaze and manual actions. Specifically, we investigated whether changes from 4 to 12 months in detailed multimodal microanalyses of this period can help to explain the "curious gap" described earlier, in terms of age-related trajectories of fine-grained joint object activity.

In the domain of joint object activity, recent studies detailing the gaze of infants and toddlers in face-to-face interactions indicate that infants spend relatively little time looking at their caregivers' faces (Deák, Krasno, Triesch, Lewis, & Sepeta, 2014). Instead, they spend the majority of time (over 50% of a play episode) looking at objects being manipulated either by their caregivers or themselves (de Barbaro, Johnson, & Deák, 2014; Deák et al., 2014; Fiser, Aslin, Lathrop, Rothkopf, & Markant, 2006; Yoshida & Smith, 2008; Yu & Smith, 2013). In a cross-sectional study, Deák et al. (2014) found that these patterns were fairly consistent in infants between 3 and 11 months, suggesting that infants' preference for watching adults' object manipulation is stable and robust, at least in dyadic play contexts. These findings differ from reports of contexts where infants are supine and objects are completely or relatively inaccessible (e.g., Kaye & Fogel, 1980; Nomikou, Rohlfing, & Szufnarowska, 2013). This contrast indicates the importance of examining dyadic attention and activity in different contexts (see also Yoshida & Burling, 2014). Recordings from naturalistic home book-sharing interactions also reveal joint object activity as early as 3 months, earlier than previously observed in laboratory settings (Rossmanith, Costall, Reichelt, López, & Reddy, 2014). At home, parents can prop up infants to support "hands-free" seated postures that afford more sophisticated dyadic object interactions (e.g., Soska & Adolph, 2014). However, the quantitative data from longitudinal free play studies have not revealed novel developmental trends across the 1st year—that is, the transition from dyadic to triadic engagement seems consistent across studies and methods. One reason might be that most studies have focused on infants' attention to the parent's actions on objects but have not also explored developmental changes in infants' manual actions, or their sensorimotor activity more generally.

We previously published a descriptive report of changes from 4 to 12 months in infants' coordination of gaze and manual object activity, and how this multimodal activity unfolds in response to parents' actions (de Barbaro, Johnson, & Deák, 2013). These changes set the stage for the complex configurations of joint object activity that are common at 12 months. For example, during imitation episodes observed at 12 months, infants often grasped and manipulated one or two objects simultaneously, and rapidly alternated gaze between those objects and others manipulated by the mother. The significance of infants distributing attention between multiple objects during shared activities has also been suggested in previous reports (Zukow-Goldring & Arbib, 2007). Namely, mothers' manipulation of objects concurrently with infants provides physical anchor or model that the infant can visually reference, promoting more successful coordination with the mother's actions. For example, infants' gaze alternations between their own objects and their mothers' objects can allow comparisons between their own object actions and those of their mother while they make online adjustments to their own manual activity (de Barbaro, Johnson, & Deák, 2013). One prominent feature of object activity at 12 months involves infants' sensorimotor decoupling. That is, during these episodes infants frequently directed their gaze and manual activity toward different toys, and even held different objects in their right and left hands simultaneously. Qualitative examinations suggested that infants showed increasingly frequent decoupling of visual and haptic modalities from 4 to 12 months. We hypothesized that infants' decoupling and rapid shifting of attention across modalities would facilitate the emergence of imitation, turn-taking games, and other shared object activities (de Barbaro, Johnson, & Deák, 2013). In particular, changes in gaze–hand and hand–hand decoupling between 6 and 12 months might allow infants to participate in these novel triadic activities, thereby potentially bridging the previously reported "gap." However, no previous study has quantified associations between changes in infants' specific multimodal action patterns and triadic action patterns.

Our goal in this study was to specify longitudinal changes in joint sensorimotor object activity from 4 to 9 months of age, using continuous, quantitative behavioral measures. In addition, we examined the dyads in a modified free play context at 12 months of age. Although this 12-month session was different enough from the previous sessions to preclude direct quantitative comparisons with the earlier sessions, it provides a crucial confirmation of the hypothesized trajectory of changes in joint object activity and in sensorimotor action patterns, and thereby provides additional empirical validation for our developmental hypotheses.

In order to test the hypothesis that sensorimotor decoupling contributes to triadic interactions, the current study quantified and modeled, in greater detail than previous studies, multimodal "streams" of infant and mother attention and action. These streams include both manual (left and right hands) and gaze activity in a setting with many possible targets, including the hands or face of the social partner and multiple objects. By defining and tracking gaze and the actions of each hand as separate modalities of activity, we can measure changes in infant decoupling, relative to various measures of joint object activity. One possible outcome is that developmental changes that are usually described in high-level cognitive terms (Carpenter et al., 1998; Tomasello, Carpenter, Call, Behne, & Moll, 2005; Trevarthen & Hubley, 1978) can be described in terms of concrete changes in sensorimotor activity.

Method

Participants

Twenty-six mother–infant dyads participated when infants were 4, 6, 9, and 12 months of age. All families participated in a larger longitudinal project of infant social attention and infant–parent interaction (Deák, Triesch, Krasno, de Barbaro, & Robledo, 2013). Data for the present analyses were collected between February 2007 and July 2009.

Families were recruited to participate in the longitudinal study through play groups, flyers, and parenting classes in San Diego County, CA, and by word of mouth. For this sample of convenience, the exclusion criteria were serious complications during pregnancy or birth, gestational age < 38 weeks, diagnosed sensory or neurological disorder, or serious chronic medical problems. All mothers were English-fluent biological parents. The 26 families included in this study were randomly chosen from among the families who had completed all four sessions by the start of the study. Due to the laborious nature of frame-by-frame analyses of naturalistic dyadic interactions, analysis of the entire sample would have exceeded our resources. However, this sample is larger than most previous studies, and it examines a broader range of behavioral variables in more detail and temporal specificity than previous studies. As a result, our final data set includes approximately 610,000 behavioral events.

The mothers averaged 31.9 years of age (range = 26 to 38 years) and had completed an average of 16.0 years of formal education (*SD* = 2.1). Most infants (65%) were firstborn, and the sample included 16 girls (62%) and 10 boys. Nineteen (76%) of the 26 participants were identified as Caucasian, 4 (15%) as multiracial or mixed ethnicity, 2 as Hispanic, and 1 as Asian.

Materials and Setting

Dyadic free play sessions took place within the families' homes. The paradigm afforded a spontaneous, dynamic flow of dyadic activity, while controlling some features across homes and sessions. At 4, 6, and 9 months of age, all infants were placed in a modified Exersaucer© walker, to control their height and posture (see Fogel, Messinger, Dickson, & Hsu, 1999). Mothers sat on a pillow on the floor (to roughly match their infant's eye height) situated so that her face was 60–70 cm from the infant's face. At each session the dyad was provided with three colorful infant-appropriate objects. At 4 months, these were a twisting caterpillar, a hard plastic toy with music-activating buttons, and a rounded wobbling/rocking animal. At 6 months, they were a foam soccer ball, a different wobbling animal, and a plastic triangle with music buttons. At 9 months, they were a foam football, a third wobbling animal, and a plastic musical rattle. Thus, object sets were roughly matched across months for size, weight, textures, shapes, colors, complexity (e.g., moving parts; sound-producing features), and animal-like or face-like features. Objects placed on the tray or in the wells on either side of the tray were within infants' reach. During the 4-, 6-, and 9-month sessions, three cameras recorded the interaction: One focused on the mother's face and upper body, another focused on the infant's face and upper body, and the third was placed further away and to the side, to provide a broader contextual view of the dyad. An example image taken from three synchronized videos is shown in Figure 1.

During the 12-month session, dyads were seated on the floor because pilot testing indicated that many 12-month-olds did not tolerate the walker. Also, because piloting revealed that 12-month-olds quickly lost interest in the toys, dyads were given a larger set of objects, including four soft colorful silicone blocks, two wooden ladybugs, and a chain of colorful plastic rings. These were placed on the floor between the dyad. The infants' increased arm length and motor control allowed them to manipulate objects without a tray. Thus, at this session as in the previous ones, infants had multiple objects within reach in addition to those held or manipulated by the mother. Two cameras recorded the 12-month sessions: One was focused on the infant's head and upper body and the other was pointed at the mother so that the infant was also visible. This positioning provided a detailed view of infants' gaze and mothers' and infants' manual object activity, but did not provide a consistently good view of the mothers' gaze direction. For this reason, we were unable to code maternal gaze at 12 months.

Angles and distances between participants and cameras were carefully matched across subjects and sessions in order to maintain video quality. Photographs and measurements of each family's playroom taken at an earlier session, and tape measures, were used to replicate the arrangement in every session. Videos were captured and synchronized in postproduction.

Procedure

At each session, an assistant set up cameras while the researcher obtained informed consent. After the mother and infant were seated they

Figure 1. Synchronized three-camera view of home play interaction.

engaged in 6–7 min of free play, followed by an attention-following task (to be described elsewhere). During the interaction the dyads were in the room alone; the researcher and assistant waited quietly out of view in another room. Mothers were instructed to "play as they normally would" with their infant, using the provided toys. At the 4-, 6-, and 9-month sessions, mothers were asked to try to keep only one toy at a time on the tray (to simplify both coding and interpretation of data), but that they should use the wells on the side of the tray to keep the three toys accessible. However, as infants became more active in manipulating objects, they spontaneously took objects from the wells; thus, there were frequently multiple objects simultaneously "in play." At 12 months, all objects were placed on the floor and mothers were not instructed to focus on a single object.

At the 4-month session, the parents and infants had seen the researcher once before, when the Bayley Scales of Infant Development, 3rd ed. was completed at the home, so they were somewhat familiar with her. At the 6-, 9-, and 12-month sessions, the dyad had participated in 3, 6, or 7 previous home sessions, respectively. They seemed comfortable with the researcher, and were familiar with the procedures. Mothers knew that the researcher was not watching the interaction. Moreover, although parents were told that the study focused on infant social development, they were not told that we were focusing on parental behaviors. These measures were designed to elicit naturalistic parental action patterns.

Coding

Videos were coded by trained undergraduate students who were unaware of the hypotheses of the study. Video coding began 5 s after the experimenter left the room and continued for approximately 3 min. From this video segment, "uncodable" video (e.g., mother rising to reposition the infant) was identified and excluded from coding. Three sessions had < 2 min of fully codable video (range = 42–66 s), and maternal gaze could not be coded from two sessions (one each at 4 and 6 months). The remaining sessions averaged 178.0 s coded from each session. In two sessions, one at 4 months and one at 6 months, it was impossible to code maternal gaze, and in three additional sessions, < 2 min were fully codable (range = 42.1–66.0 s). The remaining videos ranged from 141 to 186 s. Coders used Mangold Interact (www.mangold-international.com) to annotate target, start times, and end times of all of mothers' and infants' visual fixations and manual actions, playing the three synchronized videos at 10 frames/s. Coding reliability was calculated framewise, using Cohen's kappa (Bakeman & Quera, 2011), for sessions chosen at random to be blindly recoded by a second student.

Infant and Mother Gaze: 4–9 Months

All fixations of 0.1 s or longer were coded, from the first frame of the fixation to the frame just before the onset of a saccade away from the target. Because participants could fixate on multiple targets in close proximity, fixation targets were not mutually exclusive. Intercoder reliability for infant gaze was $\kappa = .79$ (using 22% of sample) and $\kappa = .78$ for maternal gaze (22% of sample). Possible fixation targets included:

1. *Objects*: Each object was identified.
2. *Partner's face*: Any part of the partner's head region (i.e., mother for infant gaze, or infant for mother gaze).
3. *Partner's hand*: Any part of the partner's left and/or right hand. This code was only used if the partner was not holding an object. If the partner was holding an object, gaze to held object was coded, as it not possible from remote video to reliably differentiate gaze to the holding hand, to a part of the object, or to some combination of hand and object.
4. *Partner's body*: Any part of the body except hands or face/head.
5. *Previous location*: Infant continued to gaze at the location where an object had just been, typically just after the mother removed it.
6. *Other*: All other locations and objects, including the subject's own hands, the tray, the floor, or any other features of the environment.

Infant Gaze: 12 Months

Gaze target categories coded in the 12-month sessions were the same as in the 4- to 9-month sessions. However, as noted, mothers' gaze could not be coded. Kappa for infant gaze at 12 months averaged $\kappa = .71$ (23% of sessions).

Infant and Mother Manual Object Contact: 4–12 Months

All events of 0.1 s or longer were coded, from the first frame of contact between the hand and the object to the first frame of any lapse in contact lasting longer than 1 s. This 1-s criterion prevented any inflation of the number of separate codes during repetitive touching or tapping.

Decoupling of infants' right and left hands was analyzed by identifying frames in which different objects were contacted by each hand. The same coding scheme was used for mothers and infants. Intercoder reliability averaged $\kappa = .85$ for infant manual activity between 4 and 9 months (32% of sample) and $\kappa = .84$ at 12 months (10% of sample). Kappa for maternal manual activity averaged $\kappa = .92$ at 4–9 months and $\kappa = .79$ at 12 months (both 31% of sample).

Maternal Object Motions: 4–12 Months

We coded mothers' actions to move toys "toward" or "away" from the infant, thus affecting their proximity, size, and manual accessibility to the infant. Toward actions were coded when mothers grasped an object in one of the wells and brought it to the central tray. Away actions were coded when mothers grasped an object on the tray or in the infant's hands and placed it in one of the wells. Objects movements within or above the tray space were not considered because they were more continuous and harder to code. Reliability for maternal toward and away motions averaged $\kappa = .75$ (13% of sample) at 4–9 months and $\kappa = .82$ (15% of sample) at 12 months.

Results

Methodological Considerations

All comparisons across months used repeated measures analysis of variance (rmANOVA), and included only the 4-, 6-, and 9-month sessions. All post hoc tests were Bonferroni comparisons. For all analyses, values exceeding 3 *SD* above or below the variable's mean were removed. This occurred for eight data points, or < 0.5% of the data set. For between-month comparisons, if a dyad was missing only a single data point, we imputed the missing values from the mean of the remaining dyads. If a dyad was missing more than one data point then that dyad was removed from analyses. This occurred for eight additional instances across all analyses, also < 0.5% of the data set. Additional analyses show that the findings below do not change if the missing data are not imputed.

Individual Object Activity

We first report data on changes in gaze and manual object activity of both the mother and the infant across the 1st year, as well as changes infant sensorimotor decoupling.

Infant Object Activity

The rmANOVA indicated that infants reduced object looking between 4 and 9 months, $F(2, 50) = 24.0$, $p < .001$ ($R^2 = .49$). Post hoc tests indicated significant decreases in object looking from 4 months (74.9%, $SD = 11.8$) to 6 months (64.2%, $SD = 12.7$; $p = .006$), from 6 to 9 months (52.7%, $SD = 14.1$; $p = .006$), and from 4 to 9 months ($p < .001$). For reference, at 12 months during free floor play infants spent 69.8% of time ($SD = 17.9$) looking at objects.

Infants increased object touching across the same period: rmANOVA indicated a significant effect of age, $F(2, 50) = 28.1$, $p < .00$ ($R^2 = .53$), and post hoc tests indicated significant increases from 4 (43.6%, $SD = 26.6$) to 6 (77.6%, $SD = 20.5$) months and from 4 to 9 months (83.2%, $SD = 19.4$; both *p*s < .001), but no significant difference between 6 and 9 months ($p = .69$). At the 12-month session, infants handled objects for a mean of 81.8% ($SD = 23.3$) of session time. Infants increased the amount of time they looked at and touched objects simultaneously between 4 and 9 months, as indicated by rmANOVA with Greenhouse–Geisser correction for sphericity, $F(2, 50) = 4.56$, $p = .025$ ($R^2 = .15$). Post hoc tests indicated significant increases from 4 (34.8%, $SD = 24.3$) to 6 (44.0%, $SD = 15.3$) months ($p = .04$), but no significant difference between 4 and 9 ($p = .41$) or 6 and 9 months ($p = .23$). At 12 months, infants looked at and touched objects for 61.1% ($SD = 21.8$) of the session.

Maternal Object Activity

Mothers looked at objects for an average of 39.0% of sessions (4–9 months). An rmANOVA indicated no differences in object gaze across this period, $F(2, 46) = 0.861$, $p = .43$. Mothers did, however, show a significant decline in object manipulation from 4 to 9 months, $F(2, 50) = 40.9$, $p < .001$ ($R^2 = .62$). Post hoc tests indicated significant decreases from 4 (72.4%, $SD = 16.7$) to 6 (45.4%, SD=15.6) months and from 4 to 9 (41.8%, $SD = 17.0$) months (both *p*s < .001), but no significant difference between 6 and 9 months ($p = .86$). For comparison, at

12 months mothers touched objects for an average of 76.2% (14.5) of session time. Mothers significantly decreased simultaneous looking and touching across 4–9 months, $F(2, 46) = 9.19$, $p < .001$ ($R^2 = .29$). Post hoc tests indicated significant decreases from 4 (30.0%, $SD = 10.9$) to 6 months (21.8%, $SD = 7.1$; $p = .003$) and 4 to 9 (21.6%, $SD = 10.0$) months ($p = .001$), but no difference between 6 and 9 months ($p = 1.0$; Figure 2).

Infant Sensorimotor Decoupling

Decoupling refers to infants' tendency to attend or act on multiple objects with different modalities versus converging all modalities on one object at a time. We assessed decoupling between infants' gaze and hands (GH decoupling) and between their left and right hands (HH decoupling). GH decoupling was operationalized as the proportion of frames in which gaze and at least one hand were simultaneously in contact with two different objects, out of all frames in which the infant was both looking at and touching at least one object (with at least one hand). HH decoupling was operationalized as the proportion of frames in which the two hands were touching different objects, out of all frames in which both hands were touching at least one object. Means are shown in Figure 3.

Gaze–Hands Decoupling

rmANOVA indicated significant increases in GH decoupling between 4 and 9 months, $F(2, 50) = 18.64$, $p < .001$ ($R^2 = .43$). Post hoc Bonferroni comparisons revealed significant increases between 4 (25.6% decoupled, $SD = 27.5$) and 9 (59.9%, $SD = 21.9$) months, and between 6 (28.9%, $SD = 22.0$) and 9 months (both $ps < .001$), but no significant difference between 4 and 6 months ($p = 1.0$). For reference, at 12 months infants' GH decoupling averaged 58.9% ($SD = 22.0$).

Right Hand–Left Hand Decoupling

rmANOVA showed that HH decoupling also increased between 4 and 9 months, $F(2, 50) = 12.7$, $p = .002$, corrected for sphericity ($R^2 = .34$). Post hoc tests indicated significant increases between 4 (2.0%, $SD = 3.2$) and 6 (6.5%, $SD = 9.1$) months ($p = .03$), between 6 and 9 (20.0%, $SD = 22.3$) months ($p = .02$), and between 4 and 9 months ($p = .001$). For reference, at 12 months HH decoupling averaged 39.4% (22.7).

Joint Object Activity

We considered four measures of joint object activity—two forms considering shared attention to any single object (joint activity [JA]), and two forms also considering a shared focus simultaneous with parallel activity with other objects, that is, distributed JA (dJA). We hypothesized that although dyads jointly attend to objects throughout the 1st year, infants increasingly distribute attention between their mothers' and their "own" objects across the 1st year, permitting more complex triadic interactions (de Barbaro, Johnson, & Deák, 2013).

Joint Object Activity

Our first measure of joint activity was the proportion of the session in which the mother was looking at

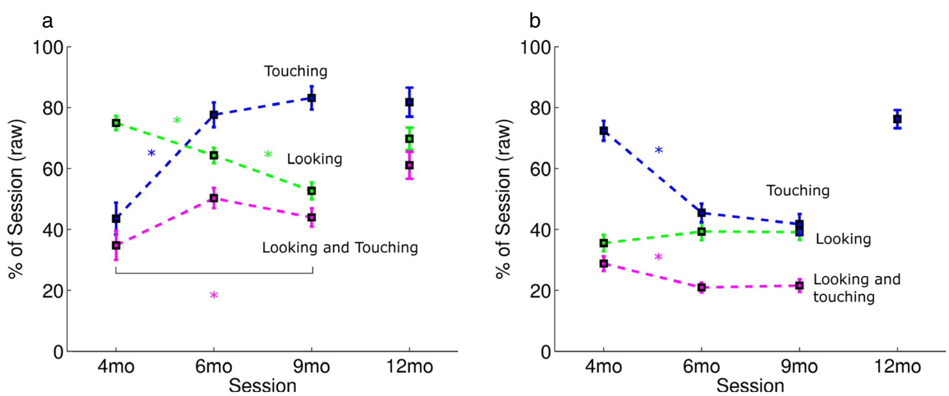

Figure 2. Infant (a) and mother (b) object activity. *y*-axis indicates raw proportion of time when given modalities were directed toward objects. Significance is determined by repeated measures analysis of variance, and differences between nonadjacent pairs are not indicated if adjacent pairs are significant. Error bars = SE_{mean}.
*$p < .05$.

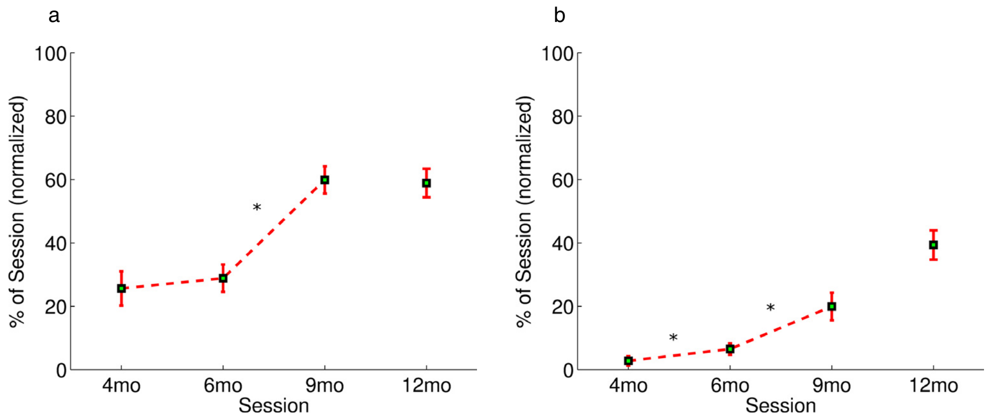

Figure 3. Changes in infant sensorimotor decoupling across 1st year. The *y*-axis indicates proportion of session that given modalities were focused on different targets. Decoupling of (a) infant gaze and hands and (b) infant right and left hands. Significance determined by repeated measures analysis of variance. Error bars = SE_{mean}.
$^*p < .05$.

or touching the same object that the infant was looking at or touching (infant looking or touching–mother looking or touching [JA:ILT–MLT]). We report both raw proportions of session time spent in this state, as well as normalized proportions, which consider only the frames in which both mother and infant were attending to at least one object via either modality (gaze or hands). The raw joint object activity averaged 60.0% (14.0) at 4 months, 46.9% (10.2) at 6 months, and 42.9.2% (14.3) at 9 months. Normalized values averaged 88% (11.3) at 4 months, 81.9% (10.4) at 6 months, and 77.2% (11.9) at 9 months. Raw joint object activity decreased from 4 to 9 months, $F(2, 50) = 17.4$, $p < .001$ ($R^2 = 41\%$). Post hoc tests indicated significant decreases in joint activity between 4 and 6 months and between 4 and 9 months (both *p*s < .001), but not between 6 and 9 months ($p = .53$). Normalized proportions show an identical pattern of results, except the difference between 4 and 6 months was only marginally significant ($p = .10$).

Our second measure of joint activity was operationalized as frames in which the infant looked at an object manipulated by the mother (infant looking–mother touching [JA:IL–MT]; Figure 4). This form might more strongly reflect infants' changing joint object participation, because infants must be looking at the mother's object, whereas in JA:ILT–MLT joint activity is also achieved if the mother looks at an object handled by the infant, for instance. Infants averaged 48% (13.4) of raw session time in JA:IL–MT at 4 months, 23.9% (9.6) at 6 months, and 20.3% (11) at 9 months. Normalized values (considering only those frames in which infants looked at objects and mothers touched objects), however, averaged 86.7% (12.0) at 4 months, 73.0% (12.7) at 6 months, and 70.5% (11.0) at 9 months, as shown in Figure 4. Time spent in JA:IL–MT decreased significantly from 4 to 9 months, both for raw values, $F(2, 50) = 52.8$, $p < .001$, $R^2 = .678$, and normalized values, $F(2, 50) = 13.97$, $p < .001$, $R^2 = .36$. Post hoc Bonferroni tests indicated that both normalized and raw JA:IL–MT significantly decreased from 4 to 6 months and from 4 to 9 months (all *p*s < .002), but not from 6 to 9 months ($p = .54$ raw, $p = 1.0$ normalized). For

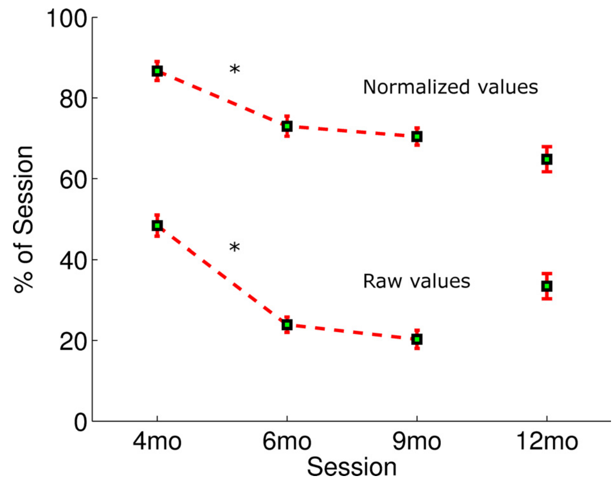

Figure 4. Mother–infant joint activity averaged over each session for each dyad. The *y*-axis indicates proportion of session time when infant looked at an object manipulated by the mother (joint activity:infant looking–mother touching). Normalized line only includes frames in which mother was touching any object and infant was looking at any object.Significance determined by repeated measures analysis of variance. Error bars = SE_{mean}.
$^*p < .05$.

reference, at 12 months JA:IL–MT averaged 33.4% (16.0) raw, or 64.8% (15.2) normalized.

Exclusive Versus Distributed Joint Object Activity

The preceding joint activity analyses indicated that infants and mothers attended to the same object more than 75% of the time when both were looking at or touching any object. In addition, the previous decoupling analyses showed increasing visual and manual decoupling with increasing age. A possible implication is that although dyads maintain a high level of joint activity across this wide age range, infants become less exclusively focused on objects manipulated by their mothers. The measures of joint activity reported above, however, do not fully address this possibility because they do not distinguish exclusive joint object activity from dJA. In the former, infants only look or touch object(s) of mother's manual or visual attention. In the latter, infants may hold one object while looking at another object held by their mother. While overall dyads show relatively high proportions of joint activity throughout the 1st year, joint activity decreases over the 1st year (see Figure 4). However, this decrease might be due to a reduction in exclusive joint attention, and dyads might nevertheless show increasing amounts of dJA. To test this hypothesis, we examined two additional measures of joint activity.

dJA: Parallel and Joint Activities

We quantified the proportion of time when infants held an object while simultaneously looking at another object manipulated by their mother, considering those times when both mother and infant touched any object. We call this parallel and joint activities (dJA:P&J). Dyads' parallel and joint activities increased with age, $F(2, 50) = 14.6$, $p < .001$ ($R^2 = .37$). Post hoc analyses confirmed significant increases from 4 (11.5%, $SD = 17.6$) to 9 (31.2%, $SD = 15.0$) months ($p < .001$), and from 6 (14.0%, $SD = 12.9$) to 9 months ($p < .001$; see Figure 5). For reference, at 12 months the proportion averaged 33.5% ($SD = 17.3$).

dJA: Response to Maternal Bids

The preceding analysis treats each action as an independent event, and thus cannot assess how sequences of actions, such as gaze shifts, contribute to changes in infants' distribution of activity between their own and their mother's objects. In the next analysis we examined infants' distributed (multimodal) response to mothers' presentations of new objects, or maternal bids (response to bids; dJA:RB). Maternal bids were naturally occurring events that punctuated the interactions and revealed infants' responses to socially constructed opportunities for joint object activity. A typical exclusive infant response to a bid is to redirect gaze and manual activity from a previously attended toy to the mother's introduced bid toy. A more distributed response by the infant is to keep holding the previous object while alternating gaze between it and the mother's novel bid object.

We defined maternal bids as instances when the mother began manipulating an object that had not been touched in the last 5 s by either her or the infant. The bid response window began when the infant attended to the bid object with either gaze or hands (see Figure 6). The window continued as long as the infant maintained attention to the bid object with any modality, and attended with any modality to any "previous" object (defined as an object that had been looked at or touched within 5 s of the bid onset). Thus, the bid ended when the infant stopped attending to either the bid object or the prior object. To allow for alternations in gaze or manual attention, "continued attention" was defined as looking at or touching the object at least once every 5 s. Thus, if the infant immediately transitioned all attentional modalities to the novel bid object and sustained that attention for at least 5 s,

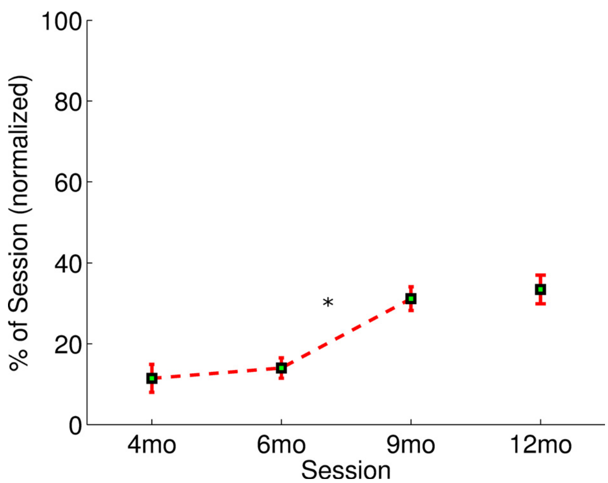

Figure 5. Distributed joint activity. Proportion of session time (*y*-axis) when infants looked at objects manipulated by mother, while holding another object (dJA:P&J). Values are averaged across dyads for each session and normalized for proportion of time infants looked at and touched any objects while mothers were holding any object. Significance determined by repeated measures analysis of variance. Error bars = SE_{mean}.
*$p < .05$.

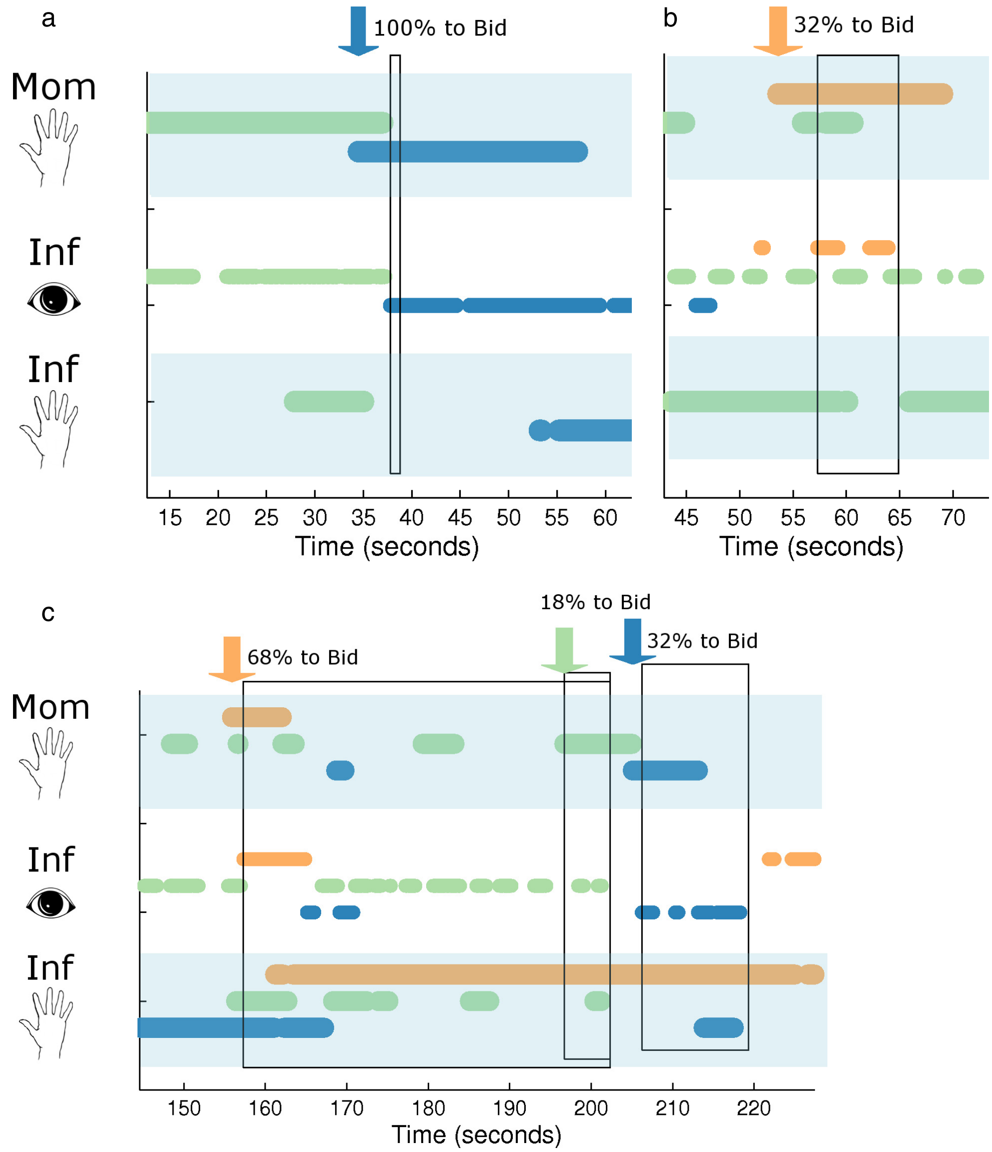

Figure 6. Figures depict typical dyadic activity in (a) 4-, (b) 6-, and (c) 9-month sessions, with maternal bids indicated. The *x*-axis indicates time (in seconds) from start of coding. Rows: Different sensorimotor modalities of infant and mother. In each row, colored bars (each color = unique object; see online version of article for Figure 6 in color) indicate when that modality focused on that object. Arrows indicate the start of a maternal bid, with identity of bid object indicated by the arrow's color. Boxes indicate the bid response window, with infant's total modality time (TMT; summed gaze and manual contact to bid object relative to all objects) noted above the box. (a) Four-month-old looks at Object 1 (denoted by green bar), then looks at and touches Object 1, then (~40 s) looks at Object 2 (blue bar)—the bid object—and then (15 s later) touches it. Infant's switch from Object 1 to 2 (bid object) follows the mother's manual switch from Object 1 to 2 (top row). Thus, infant's switch to the bid object ends all contact with Object 1, creating a short bid response window and 100% TMT. (b) Six-month-old maintains gaze and manual contact to the bid object (orange), and to a previously attended toy (green) during the bid response. TMT = 32%. (c) Nine-month-old touches multiple objects simultaneously across three bids that produce TMTs ranging from 18% to 63%. Over the 1st year, modalities become increasingly distributed across more objects (i.e., bid and "other"), and bid responses become longer as infants increasingly distribute attention.

the response window was minimal. Short windows therefore reflected a quick resolution of conflict for attention between the new bid object and previous objects (see Figure 6a). By contrast, if the infant continued to look at or touch both the new bid object and previous objects (simultaneously or in fairly quick succession), the window lengthened, reflecting distributed attention between objects (Figure 6b and c). Thus, the bid response window was determined by the infant's activity and not by the mother's ongoing activity. We operationalized the measure in this way because we observed that infants often held and manipulated a bid object after it was introduced.

Mothers averaged 2.7 bids per session (SD = 2.2). This number of bids did not differ significantly across 4- to 9-month sessions, $F(2, 50) = 0.313$, $p = .73$. However, the infant bid *response* duration differed marginally across sessions, $F(2, 30) = 3.06$, $p = .062$. Post hoc comparisons revealed that 9-month durations (12.0 s, SD = 7.3) were longer than 4-month responses (7.2 s, SD = 6.4; $p = .01$). No other session means differed. At 12 months, mothers averaged 10.9 (SD = 7.1) bids per session, and infant response windows averaged 9.9 s (SD = 5.3).

Within each bid response window we characterized the distributed versus exclusive nature of infants' contact with the mother's bid object relative to other objects. This was calculated as the proportion of total time, within the bid response window, when infants' modalities (defined as gaze, left hand, and right hand, each treated as an independent addend) were directed at the bid object, out of the total time when the modalities were directed at any object. A higher proportion of contact directed toward the bid object indicates a more exclusive bid response. Figure 7 shows histograms of proportions of bid–object contact, for all bids in each session month.

Because the distributions of these proportions were skewed, the median proportion of total bid–object contact, for each infant within a given session, was entered into an rmANOVA. Infants' showed reduced proportions of attention to bid objects relative to other objects with increasing age, indicating more distributed responses when the parent presents a new object for examination, $F(2, 44) = 9.24$, $p < .001$ ($R^2 = .30$). Post hoc tests indicated higher proportions of bid object contact at 4 months (79.7%, SD = 28.4) than at 6 months (58.6%, SD = 23.0; $p = .03$), or 9 months (46.8.0%,

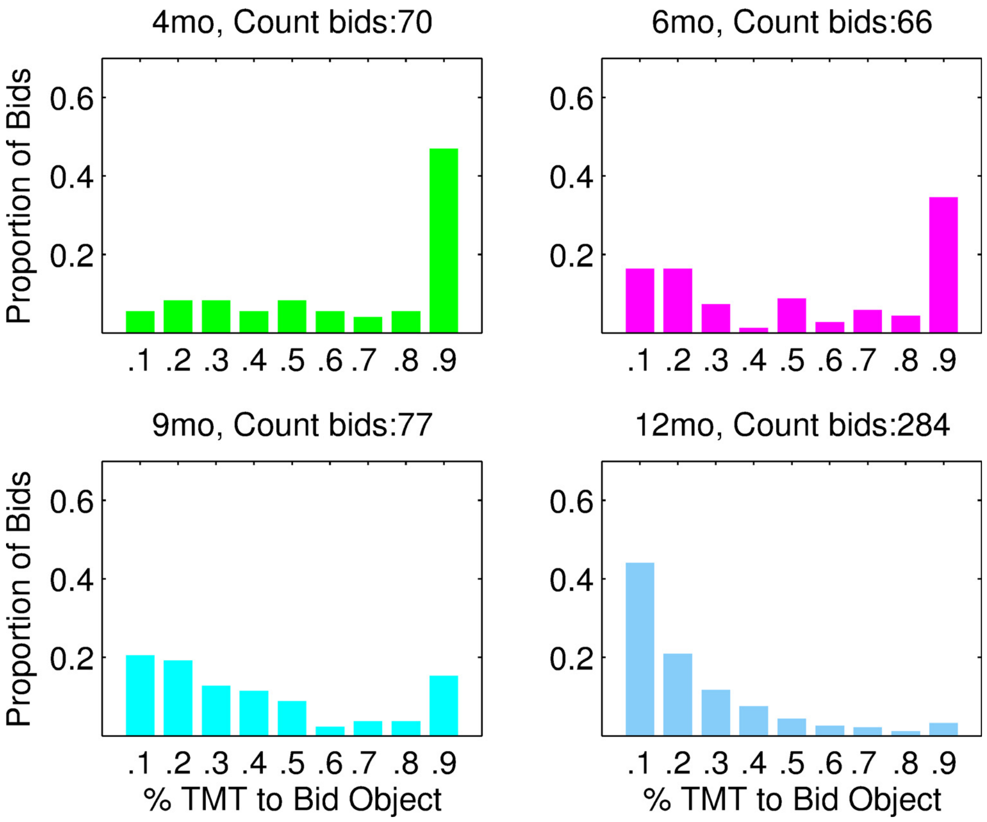

Figure 7. Histograms of infants' proportional of contact with maternal bid objects during all bids at 4-, 6-, 9- and 12-month sessions (left to right, top to bottom). Each *x*-axis delineates a histogram of total modality time to the bid object, in 10% bins (total modality time [TMT]; see text), as a proportion of attention to all available object(s). The *y*-axis indicates proportion of all bids within a given bin. The rightmost bin indicates the most exclusive focus of activity on (90%+ contact) the maternal bid object, whereas the leftmost bins indicate that gaze and manual activity are distributed between the bid object and other objects (decreasing contact with the bid object). From 4 to 9 months, the histograms shift from exclusive bid object attention to more distributed attention. At 12 months, the histogram is heavily skewed toward multimodally distributed attention.

SD = 22.4; *p* = .003), but no difference between 6 and 9 months (*p* = .40).

Can Mothers' Activity Explain Infants' Sensorimotor Changes?

One possible explanation for the preceding results is that changes in infants' sensorimotor activity are a by-product of maternal activity. Specifically, mothers may facilitate younger infants' focus on single objects by making only one object available at a time to the infant, whereas later, when infants are older, mothers might present more objects, thus facilitating distributed attention. We assessed this possibility by examining the rate at which mothers moved objects toward and away from infants' area of reach. The rate of object motion toward infants did not change across 4- to 9-month sessions, $F(2, 50) = 1.85$, $p = .17$. The rate of object removal marginally increased across 4- to 9-month sessions, suggesting that mothers did not overall make more objects available for older infants, $F(2, 50) = 2.7$, $p = .08$ ($R^2 = .10$). Post hoc Bonferroni comparisons revealed marginally more frequent object removal at 4 months (*M* = 1.37/min, *SD* = 1.2) than 9 months (*M* = 1.91/min, *SD* = 0.89; *p* = .09), but no other differences between sessions (all *p*s > .62).

Correlations Between Decoupling and Dyadic Activity Distribution

Within each month we correlated decoupling scores with measures of joint object activity and mother's object activity. Because the majority of these variables had skewed distributions, we used nonparametric Spearman's correlations. Results are shown in Tables 1 and 2. They indicate that increases in both GH and HH decoupling are associated with (a) lower proportions of time spent in simple joint activity, notably at 4 and 6 months, that is, less time attending to objects held by mother (JA:ILT–MLT and JA:IL–MT); (b) higher proportions of simultaneous parallel and joint activities, at all ages, that is, more infant looking at mother-held object while holding own object: dJA:P&J); and (c) more distributed object attention in response to mothers' bids (dJA:RB).

One possibility might be that mothers showed increasing multimodal activity, and this drove infants' attention decoupling. However, the proportion of time mothers spent looking at or touching objects was not significantly correlated with infant GH or HH decoupling. It is also possible that the rate of mothers' object motion toward and away

Table 1
Correlations With Gaze and Hands Decoupling Values Month by Month

	4 months	6 months	9 months	12 months
HH decoupling	0.33	**0.58***	**0.753***	**0.74***
JA:ILT–MLT	**−0.58***	**−0.72***	0.02	N/A
JA:IL–MT	**−0.58***	**−0.63***	0.24	**−0.4**
dJA:P&J	**0.77***	**0.75***	**0.74***	**0.59***
dJA:RB (RS)	**0.47***	0.3	**0.42**	0.31
Mom obj looking %	0.12	−0.25	0.38	N/A
Mom obj touching %	0.02	0.17	0.23	0.13
Mom rate "toward"	0.33	0.06	−0.12	0.10
Mom rate "away"	0.06	0.10	0.28	−0.10

Note. All correlations significant at $p < .05$ are marked in bold and all correlations significant at $p < .01$ are indicated by an asterisk (*). Values marked as N/A are due to lack of mothers' gaze data at 12-month sessions. HH = right hand–left hand decoupling; JA = joint activity; dJA = distributed joint activity; ILT–MLT = infant looking or touching–mother looking or touching; IL–MT = infant looking–mother touching; P&J = parallel and joint activities; RB (RS) = response to bid, reverse scored, such that higher scores indicate more distributed responses to bid; obj = object.

Table 2
Correlations With HH Decoupling Values Month by Month

	4 months	6 months	9 months	12 months
JA:ILT–MLT	−0.28	**−0.49**	0	N/A
JA:IL–MT	−0.36	**−0.62***	0.17	−0.34
dJA:P&J	**0.55**	**0.62***	**0.633***	**0.48**
dJA:RB (RS)	0.20	0.31	**0.52**	0.3
Mom obj looking %	**0.50**	−0.12	0.25	N/A
Mom obj touching %	0.10	−0.04	0.23	−0.23
Mom rate "toward"	0.30	**0.47**	−0.10	−0.10
Mom rate "away"	.07	**0.44**	0.14	0.01

Note. All correlations significant at $p < .05$ are marked in bold and all correlations significant at $p < .01$ are indicated by an asterisk (*). Values marked N/A are due to lack of mothers' gaze data at 12-month sessions. HH = right hand–left hand decoupling; JA = joint activity; dJA = distributed joint activity; ILT–MLT = infant looking or touching–mother looking or touching; IL–MT = infant looking–mother touching; P&J = parallel and joint activities; RB (RS) = response to bid, reverse scored, such that higher scores indicate more distributed responses to bid; obj = object.

from the wells was associated with infants decoupling. Mothers' rate of object motion was positively associated with HH decoupling at 6 months, but not with any other decoupling measure at any other session. Thus, this cannot account for the overall pattern of increasing decoupling with age.

Discussion

This study characterized the dynamics of sensorimotor activity during infant–parent free play with objects, specifying all changes in gaze and manual attention. By quantifying activity between 4 and 9 months, we characterize a gradual transition in patterns of triadic activity (see the summary in Table 3). These trajectories provide a novel account of how the 9-month "revolution" emerges from continuous changes in coordinated and distributed multimodal activity.

Some aspects of sensorimotor attention and joint activity were constant across age. At all ages, infants showed an active interest in objects via gaze and manual activity. Additionally, in every session infants and their mothers gazed at and manipulated objects together, jointly attending to objects over 80% of times when both participants were attending to any objects. Moreover, contrary to previous work that highlighted younger infants' preoccupation with face-to-face contact, our results show that 4-month-old infants spent over 40% of raw session time manually contacting objects and 75% of session time looking at objects, and that simple joint object attention was actually in the *highest* proportion at the 4-month session, and decreased across the 1st year. Although these results appear to contradict previous findings, many of those previous studies did not include objects (e.g., Hsu & Fogel, 2003; Kaye & Fogel, 1980) or, if objects were present, situated infants so that they would have difficulty independently looking at and touching the objects (e.g., Nomikou et al., 2013). Our results are consistent with other studies that examined face-to-face interactions with objects where infants were seated upright, allowing the possibility of independent interaction with objects. Under such conditions, Deák et al. (2014) also found that 3- to 5-month-old infants were approximately 5 times more likely to look at objects manipulated by parents than at their parents' faces. That tendency persists through the 1st year (Deák et al., 2014) and has also been reported in 1-year-old toddlers (Yoshida & Smith, 2008; Yu & Smith, 2013). In this sense, interactions are actually triadic from the youngest age we studied: At 4 months, the infants actively engaged in object exploration, with their mothers' scaffolding (see also de Barbaro, Johnson, & Deák, 2013; Rossmanith et al., 2014). However, the nature of infant object activity across sessions changed considerably, particularly with regard to manual activity and gaze–hand coordination. Furthermore, these changes in sensorimotor object coordination had implications for mother–infant joint object play.

Table 3
Summary Table

Longitudinal trends in triadic activity across 1st year:
- More decoupling of sensory modalities
- Less joint looking and touching activity
- More distributed activity between infant's own toys and mother's toys

At each month, more decoupling is associated with:
- Less joint looking and touching activity
- Less exclusive attention to mother's object actions

Continuous trajectories from 4 to 9 months can "bridge the gap" in coordinated joint activity

First, we observed a decrease in infants' looking at objects from 4 to 9 months, amounting to an average of approximately 20% of the session time. Further analyses (not reported here) showed no compensatory increase in average time spent looking at mother's face (de Barbaro et al., 2014); rather, infants increasingly looked at other features of their environments (e.g., tray, floor, and furniture). At 12 months, object looking returned to relatively high proportions—one of the only trends from 4 to 9 months that did not continue to 12 months. We attribute this discontinuity to the change in paradigm at 12 months, when a larger set of toys was placed on the floor in front of infants and, because they were sitting unsupported on the floor, infants had to look up at a sharp angle to see most other salient targets, including the mother's face.

Second, there were large and significant increases in infant manual object contact from 4 to 6 months. These correspond to the development of infants' ability to independently reach for and grasp objects (e.g., Rochat & Goubet, 1995). Infants' increasing autonomy in manipulating and moving objects might contribute to our finding that overall proportions of joint object activity reliably decreased between 4 and 6 months.

Our results suggest that infants' challenge in joint play in the second half of the 1st year is not in attending to objects manipulated by caregivers, but rather in learning to incorporate attention to caregiver's objects into their own burgeoning object activity. Infants from 4 months on already attend to objects manipulated by their mothers. However, from 6 months through the end of the 1st year, infants show increasing manipulation of other available objects, while still attending to objects presented or handled by a caregiver. In two different analyses, we quantified changes in infants' multimodal activity with objects manipulated by mothers. The results show increasingly distributed attention between infants' own objects and mothers' objects, starting at 6 months.

For example, from 6 to 9 months infants increasingly watch their mother manipulate objects while they keep manual contact with other objects. This sort of distributed object activity was also reflected in infants' multimodal responses to maternal object bids. At 4 months, infants typically shifted all modalities to any bid object, and terminated attention to previously attended objects. Thus, 4-month-olds' object attention was largely directed by mothers' activity, and their engagement with multiple objects was infrequent and unstable. By 9 months, infants increasingly distributed their sensorimotor modalities between maternal bid objects and other available objects. Note that the duration of bids increased from 4 to 9 months, so this increase in attention distribution does not simply indicate that older infants tend to ignore bids or rapidly terminate joint attention episodes. Rather, it specifically indicates a tendency to distribute attention between a partner's object of attention and other objects of the infant's own ongoing activity.

Infants' increasing decoupling of attentional modalities toward multiple objects might have implications for change joint object play. Decoupling modalities (gaze, left hand, and right hand) allows infants to watch their mothers' object activity while maintaining contact with their own objects. This sets the stage for activities like taking turns using toys or attempting to imitate the mother's actions. Decoupling might also facilitate faster gaze shifting between infants' own objects and their partner's objects. We are exploring this possibility in ongoing work.

Within-session analyses of individual dyads indicate that increased sensorimotor decoupling is associated with less simple joint object activity (JA:ILT–MLT; JA:IL–MT) and more distributed joint object activity (e.g., looking at mother's object while handling one's own, dJA:P&J; dJA:RB). These relations changed across the 1st year, in different trajectories for different modalities and joint attentional activity. Specifically, both GH and HH decoupling were most strongly negatively correlated with simple joint object activity (e.g., JA:IL–MT) at 4 and 6 months. This may reflect that decoupling early on is more likely to allow infants to shift attention away from objects presented by a social partner. From 6 to 9 months, decoupling may also allow infants to maintain attention to objects manipulated by the mother, as indicated by increasing parallel and joint activities (dJA:P&J). This could diminish the strength of correlations between simple joint activity and decoupling at 9 and 12 months. However, across all ages, more decoupling predicts more distributed joint object activity, as indicated by the consistent relations with distributed parallel and joint activities (dJA:P&J), and a significant positive relation at 9 months to more distributed bid responses (dJA:RB). Overall, moreover, there were stronger correlations for GH than HH decoupling. Infant looking to objects held by the mother may be a more common form of distributing joint object activity than touching an object held by the mother. Additionally, while moments of GH decoupling do not always contribute to parallel and joint activities, by definition this measure requires infants to decouple gaze from hands.

Thus, across the 1st year infants do not simply attend more and more to the mother's activity, rather they increasingly coordinate and alternate their activity between their mothers' and their own object actions. Sensorimotor decoupling is a *gradual* developmental product that contributes to more distributed joint object activity.

Role of the Mother

Infant sensorimotor activity is an outcome of a dynamic system including social partners and broader ecological variables (e.g., Deák et al., 2014; Yoshida & Burling, 2014). One possibility is that changes in the mothers' activity across the 1st year account for changes in infants' distribution of attention and decoupling. However, the data do not support this. Mothers *reduced* their manual activity across sessions, their rate of presenting objects remained constant over sessions, and their rate of removing objects marginally *increased*. These changes could have served to *focus* infants' attention, but instead infants showed increasing distribution of attention. Additionally, from session to session, the frequency with which mothers moved toys toward infants or removed them was not associated with any measure of decoupling, except for two correlations between the rate of moving toys toward and away from infants and HH decoupling at 6 months. Our qualitative analyses (de Barbaro, Johnson, & Deák, 2013) suggest that this might be due to mothers' attempts to maintain a single toy on the tray while their infants exercised their new skills at reaching for and grasping additional toys—that is, even this correlation might have been partly attributable to infants' expanding sensorimotor independence. Indeed, one question is whether we might have seen more decoupling at 4–6 months if mothers had not been discouraged from keeping multiple objects in play. Overall, although our data show that mothers and infants do comodulate one another's activity, the increases in sensorimotor decoupling across sessions cannot be fully explained by changes in mothers' object activity or motions.

Relations to Previous Work

Although our analyses focused on changes in decoupling, other work suggests that gaze–hand coupling is important for infants' learning about object properties (Soska & Adolph, 2014; Soska, Adolph, & Johnson, 2010). In particular, gaze–hand coupling may help to override "default" symmetry of motor actions (Soska, Galeon, & Adolph, 2012). Additional analyses (not reported above) indicate that the proportion of session time infants spent with GH coupled, that is, looking at an object they were simultaneously manipulating, marginally increased ($p < .07$) between 4 and 6 months. Thus, between 4 and 6 months both gaze–hands decoupling and gaze–hands coupling increase (these are partly independent because an infant can have an object in each hand). Interestingly, however, GH coupling decreased between 6 and 9 months ($p < .001$), suggesting that GH coupling becomes less important in late months. Perhaps this is because infants require less time to assess object properties, or perhaps this is because learning intermodal mappings between motor, haptic, and proprioceptive feedback allows infants to execute more effective object handling without visual guidance. Another possibility is that infants may become less interested in the perceptual features of objects and more interested in activities afforded by the objects that may not require gaze–hand coordination (Baumgartner & Oakes, 2011).

In addition, previous studies have noted an increase in multiple-object handling in the second half of the 1st year (Kotwica, Ferre, & Michel, 2008; see also Bruner, 1973; Fenson, Kagan, Kearsley, & Zelazo, 1976). However, those studies observed infants' independent object activities rather than object activity in the context of social interactions. Our study complements that work by specifying how changes in distributed multimodal activity affect the trajectory of triadic attending. Although infants can effectively reach for and manipulate objects by 6 months of age, additional developments in *multiobject* activity occur between 6 and 9 months, concurrent with the purported "gap" in the development of shared-object attending (Adamson & Bakeman, 1991).

At 12 months, the same features of sensorimotor activity that increased at 6 and 9 months were observed in a slightly modified, more age-appropriate play context. In particular, during 12-month sessions, infants' modalities were highly decoupled, and infants' attention to mother-presented objects was highly distributed. Distributing sensorimotor modalities between multiple objects—in particular, between objects held by the parent and those held by the infant—is a core feature of complex joint object activities such as turn-taking games, imitation, and acquisition of tool-using skills (de Barbaro, Johnson, & Deák, 2013; Zukow-Goldring & Arbib, 2007). In such activities infants both observe the partners' actions on objects and act upon objects themselves. The trajectories found here suggest that changes in multiobject attending contribute to patterns of triadic interaction that are developing during the "gap" or latency period in joint object activity.

Limitations

The current findings should be interpreted with respect to several limitations. First, procedural differences between the 4- through 9-month sessions and the 12-month session prevent any direct comparison of earlier sessions with the last session. Nevertheless, almost all of the results from the 12-month session fit the trends established across the earlier sessions, and the rare exception (i.e., an increase in object-directed gaze at 12 months) is readily explained by the switch to a novel observational context. Nonetheless, in a future study it would be ideal to find an observational context that allows age-appropriate and direct comparison of 9- and 12-month-olds' sensorimotor dynamics during dyadic toy play.

A second limitation arises from the fact that our results from 4 to 9 months were taken from observations in a single context. Because our analyses focus on how agents move their bodies and direct their sensorimotor modalities to objects in space, the physical context of the environment is critical. The patterns we observed might differ in other contexts (e.g., Nomikou et al., 2013; Yoshida & Burling, 2014) and in other cultures (e.g., Bakeman, Adamson, Konner, & Barr, 1990). In designing the free play paradigm for this study, we opted for a controlled but free-flowing situation to elicit and observe shared actions on objects. However, it would be ideal to replicate the results in additional object play contexts.

Developmental Accounts of Triadic Attention

Our results indicate quantitative changes from 4 to 9 months in the dynamics of infants' sensorimotor activity while attending to and engaging with caregivers and objects. The processes described here are not mutually exclusive with a qualitative shift in early social interactions. Indeed, one principle of complex systems is that quantitative shifts in component processes can result in qualitative shifts in system activity (Spencer & Perone, 2008). However, the results do call into question a conventional theory in which triadic activity follows a representational "shift": namely, a new ability to infer the intentions of a social partner (Striano & Reid, 2006; Tomasello et al., 2005). Some scholars describe this shift as a "social revolution" (Tomasello, 1999) or the birth of "secondary intersubjectivity" (Trevarthen & Hubley, 1978). This latter term refers to a new a conceptual ability to infer the subjective experiences and mental states of others, and the related notion that people's activity is driven by these mental states. These theories make strong claims for a representational, conceptual basis for the emergence of triadic interaction skills.

One reason that previous accounts described a "revolution" is that previous longitudinal studies of infant–parent interactions operationalized and coded dyadic- or triadic-level states such as joint attention to an object or infant solo play (e.g., Bakeman & Adamson, 1984; Hsu & Fogel, 2003). However, such coding schemes, applied at low sampling rates, give the impression that novel triadic states appear rather abruptly, suggesting a discrete developmental shift (e.g., Stern, 1985; Tomasello, 1999; Trevarthen & Hubley, 1978). Such high-level coding schemes also ignore the low-level sensorimotor processes from which macrolevel behavioral shifts could emerge.

By coding behavior in more detail, our data reveal trajectories that had not been previously considered. First and foremost, the results indicate that developments in triadic activity require more than just a conceptual or representational shift. At a minimum, triadic activity also requires changes in multimodal sensorimotor coordination. Thus, any account of the development of social attention should include an account of the developing multimodal sensorimotor coordination by which infants engage with objects and people.

Another possibility raised by our results is that the emergence of triadic activity may not require any internal shift in representing mental states of others but, rather, might emerge from interpersonal coordination of activity. For example, by distributing attention more rapidly and fluidly between their mothers' and their own actions on objects, infants gain access to, and eventually predict, action patterns that allow participation in increasingly complex triadic activities such as imitation and turn-taking games. We have previously discussed this possibility in light of several other trajectories observed in this data set (de Barbaro, Johnson, & Deák, 2013). A related position has been articulated by researchers who construe intentionality as developing out of the practices of joint activity, rather than the sharing of mental states preceding or being a precursor for joint activity (Carpendale & Lewis, 2004, 2010; Fogel, 1993; Rączaszek-Leonardi, Nomikou, & Rohlfing, 2013; Reddy, 2008). In such a framework, shared understanding is a developmental achievement that emerges over time through embodied joint activities, as infants increasingly learn to anticipate and respond to a partner's familiar activity patterns.

The results presented here illustrate that the increasing complexity of social interactions in the 1st year of life can be revealed by detailed analyses of the dynamics of infants' and caregivers' activity with one another and their environments, and in their adaptive actions and reactions. This and other examples (Deák et al., 2014; Goldstein & Schwade, 2008; Jasso Triesch, Deak & Lewis, 2012; Yu & Smith, 2013) demonstrate the potential for microbehavioral and sequential analyses to answer questions about the development of complex social activity. Although changing patterns of brain activity during social interactions remains elusive (but see Liao, Acar, Makeig, & Deák, 2015), and higher order mental representations remain hypothetical, sensorimotor activity between partners is overtly measurable and rich. By focusing on changes in the microbehavioral dynamics of dyadic sensorimotor activity of infants and parents in natural settings over the 1st year, we can construct a new, more ecologically grounded account of the development of triadic attention and other social practices.

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