Title
Variability in Infant Social Responsiveness: Age and Situational Differences in Attention-Following

Authors
Tang, Yueyan
Triesch, Jochen
Deák, Gedeon O

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Infant Sensorimotor Decoupling From 4 To 9 Months Of Age: Individual Differences And Contingencies With Maternal Actions

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Corresponding Author:	Gedeon Deak, PhD La Jolla, CA United States
First Author:	Zhuojun Ying
Order of Authors:	Zhuojun Ying
	Betina Karshaleva
	Gedeon Deak
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Suggested Reviewers:	Daniela Corbetta, Ph.D. Professor, The University of Tennessee Knoxville dcorbett@utk.edu Dr. Corbetta is an expert in perceptual and motor development.
	Jeffrey Lockman, Ph.D. Research Professor, Tulane University lockman@tulane.edu Dr. Lockman is an expert in perception-action and cognitive development.
	John Franchak, Ph.D. Associate Professor, University of California Riverside franchak@ucr.edu Dr. Franchak is an expert in perceptual-motor development
	Ty Boyer, Ph.D. Professor, Georgia Southern University tboyer@georgiasouthern.edu Dr. Boyer is an expert in child development and action perception.
	Hanako Yoshida, Ph.D. Associate Professor, University of Houston yoshida@uh.edu

	Dr. Yoshida is an expert in child development and social attention.
	Brianna Kaplan New York University brianna.kaplan@nyu.edu Dr.Kaplan specializes in infant object interactions and multimodal joint activities.
Opposed Reviewers:	

Highlights

- Infants increasingly decouple sensorimotor modalities (hands; gaze) from 4-9 months
- Decoupling is contingent on caregivers' manual actions
- Decoupling is associated with infants' motor and communication skills
- There are individual differences in the trajectories of individual infants' decoupling rates
- Social contingent decoupling rates predict the developmental trajectory of infants' overall decoupling rates

Abstract

Triadic interactions, wherein infants coordinate attention between caregivers and objects of shared focus, are believed to facilitate learning. Triadic engagement was believed to emerge around 9-12 months of age (Carpenter, Nagell, & Tomasello, 1998). Sensorimotor decoupling, wherein infants look at one percept while manipulating another, or use each hand for different actions, was hypothesized (de Barbaro et al., 2016) to contribute to triadic skills by allowing infants to smoothly shift attention between objects and social partners. We explored the development of Hand-Hand (H-H) and Gaze-Hand (G-H) decoupling in 38 infants at 4, 6, and 9 months. We also tested contingencies between maternal behaviors and infant decoupling: i.e., whether decoupling events followed maternal object-directed actions. Both overall and contingent infant decoupling increased from 4 to 9 months. In addition, we characterized individual differences in infants' longitudinal development trajectories and related these differences to infants' later motor and communication skills. Decoupling rates (both G-H and H-H) predicted variance in infants' fine and gross motor scores. Contingent G-H decoupling at 6 months predicted BSID-III communication scores at 18 months. Thus the development of infant sensorimotor skills, including decoupling, allows infants to smoothly shift attention and participate in triadic interactions.

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Infant Sensorimotor Decoupling From 4 To 9 Months Of Age: Individual Differences And Contingencies With Maternal Actions

Zhuojun Ying, Betina Karshaleva, and Gedeon Deak

Department of Cognitive Science, University of California - San Diego

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1. Introduction

Caregiver-infant triadic interactions, wherein an infant coordinates attention between a social partner and objects of shared attention (Striano & Reid, 2005), facilitate infants' learning of social and praxis (e.g., tool-using) skills. These skills include intentional actions on objects (Brandone, Stout, & Moty, 2019), word comprehension (Carpenter, Nagell, & Tomasello, 1998), attention-following (Striano & Reid, 2005), and social routines (Rochat et al., 2016). During the first year infants increasingly coordinate their attention with caregivers, and shift attention between caregivers and objects during shared activities (Rossmanith et al., 2014). These triadic interactions, it is argued (Tomasello, 1999), represent a watershed in social development.

It is commonly claimed that triadic engagement emerges around 9 to 12 months of age (Carpenter et al., 1998), following a period when infants can participate only in *dyadic* interactions: that is, attending to either a partner or an object, but not coordinating reciprocal attention-switches between them. However, there is ongoing debate regarding the qualitative "sharpness" of this developmental change (de Barbaro et al., 2016), and the factors driving it. Some studies suggest that earlier-emerging social and motor advances contribute to triadic interaction skills (Mundy et al., 2007; Nichols et al., 2005). For example, Striano & Rochat (1999) reported an association between infant triadic skills (e.g.joint engagement; attention monitoring) and earlier (7 month) dyadic social competencies.

Other, more general, cognitive precursors have also been proposed. De Barbaro et al. (2016) suggested that triadic interactions emerge partly as byproducts of changing perceptual-motor and attention-regulation behaviors, including sensorimotor decoupling. De Barbaro et al. argue that triadic attention relies on flexibly shifting attention between an interlocutor (e.g., caregiver) and objects that person is manipulating (Deák et al, 2014), and other objects (e.g., that the infant is holding). Evidence consistent with this hypothesis includes findings that infants from 2 to 6 months improve at shifting attention to exogenous events (Hunnius & Geuze, 2004; Matsuzawa & Shimojo, 1997). Such shifting is arguably a prerequisite of attention-shifting in triadic interactions. Also, from 4 to 12 months infants increasingly decouple their sensorimotor modalities (e.g., gaze; left hand; right hand; e.g., de Barbaro et al., 2016). Decoupling allows infants to look at one percept while manipulating another, or to use each hand for different actions or objects (de Barbaro et al., 2016). These findings indicate that maturation of attentional and decoupling abilities coincides with the emergence of triadic attention.

De Barbaro et al. (2016) hypothesized that development of decoupling from 4 to 12 months might facilitate triadic interactions. Around 3-5 months, infants often bring both hands to their midline to manipulate or grasp an object placed within reach by an adult (Corbetta & Thelen, 1996). Subsequently, from 6 to 12 months, infants increasingly decouple their hands for bimanual activities (Fagard & Pezé, 1997), simultaneously engaging with multiple objects that they or their caregivers hold (de Barbaro et al., 2013). This decoupling allows infants to co-manipulate an object with a caregiver while maintaining manual control over another object.

Our goal is to investigate the hypothesis that maternal toy manipulation scaffolds infant sensorimotor decoupling. De Barbaro et al. (2013) showed that mothers adjust their object bids as infants' sensorimotor responses become more mature (from 4 to 12 months). De Barbaro et al. observed that mothers extensively used manual activities to scaffold infant toy manipulation at 4 months, and this scaffolding decreased by 12 months. However, the relation between these changes in maternal toy handling and the development of sensorimotor decoupling remain unclear. In order to test whether maternal actions facilitate infant sensorimotor decoupling, using the same behavioral data as de Barbaro et al. (2013), we measured longitudinal changes in the frequency and nature of infant sensorimotor decoupling, and examined the subset of decoupling episodes that were temporally contingent on maternal toy-handling actions.

We also aim to identify individual differences in the developmental trajectories of sensorimotor decoupling. De Barbaro et al. (2013) suggested that around 6 months infants are in a transitional period for decoupling skills. They divided infants into High and Low Decoupling groups, based on a median split of Gaze-Hand decoupling rates at 6 months. Infants in the High group showed 6-month decoupling rates comparable to group average at 9 months, whereas infants in the Low group showed 6-month rates similar to the group average at 4 months. However, it is unknown whether a median-split classification is the best predictor of individual decoupling trajectories. Therefore, here we use a bottom-up, data-driven method to classify infants into subgroups with faster versus slower trajectories for each of two types of decoupling: Gaze-Hand and Hand-Hand. We then test whether group classification predicts other infant skills that might interact with sensorimotor decoupling, notably, motor and communication development. These analyses extend the results reported by de Barbaro et al (2013; 2016), and make this study one of the few to explore associations between micro-level maternal actions and longitudinal changes in infant motor and communication skills.

1.1. Gaze-Hand decoupling

As infants' perception-action coordination improves, their decoupling of visual and haptic sensorimotor modalities increases. For example, infants' reliance on visual guidance during reaching declines after 7 months (Bushnell, 1985). The development of visual and haptic control allows infants to more effectively distribute visual and haptic attention to explore features of their environment (Corbetta et al., 2000). This developing control might also influence attention in social interactions (de Barbaro et al, 2013). For example, 9-month-old infants can manipulate an object while visually sampling and anticipating a caregiver's reaching action (Monroy et al., 2020).

1.2. Hand-Hand decoupling

At a young age, infants tend to converge both hands on a single object. However, infants show preference for a dominant hand as early as 4 months (Morange & Bloch, 1996), and their tendency to converge hands on an object declines by 5 months (Bresson et al., 1976). Thus, with age infants increasingly use their hands independently, for different purposes (Bresson et al., 1976; Kotwica, Ferre & Michel, 2008).

1.3. Social Contingencies and Infant Sensorimotor Decoupling

These changes in decoupling might be moderated by social events and sequences. Contingent responses are a key component of mother-infant social interactions. Mothers can reliably respond within a second to infants' communicative signals during face-to-face interactions (Keller et. al, 1999). Infants in turn are sensitive to contingencies in mother-infant interactions, by two months or earlier (e.g., Bigelow & Rochat, 2006; Kaye & Fogel, 1980). Furthermore, infant signals are contingent on mothers' language and gestures (Kuchirko et.al, 2018): temporal coordination between adult vocalization and infant gaze has even been reported as early as 6 weeks (Crown, Cynthia, et al., 2002). However, little is known about how infants modify their sensorimotor exploration in response to caregivers' actions. De Barbaro et al. (2013; 2016) hypothesized that as infants age from 4 to 12 months, mothers tend to adjust their object-related bids and infants' action responses become more elaborate and controlled. This suggests that developmentally appropriate caregiver actions - including actions with objects - might modulate infants' contingent sensorimotor responses, which could include decoupling. Thus, infant decoupling might develop partly in response to maternal bids during triadic interactions.

There is some evidence consistent with this hypothesis. For example, during triadic interactions at twelve months, both infants and caregivers coordinate visual attention to objects jointly manipulated by both participants (Yu & Smith, 2013; Frischen, Bayliss & Tipper, 2007). However, from 8 to 12 months infants increasingly shift attention to objects handled by the parent (Boyer, Harding & Bertenthal, 2020). If this increase in attending to caregivers' object-handling (Deák et al., 2014) were found to predict increasing sensorimotor decoupling, it would constitute a previously unestablished connection between social attention and motor development (Adolph & Hoch, 2019). Indeed, there is evidence consistent with this connection for example, infants are more sensitive to adults' reaches after receiving ‘sticky mittens’ training to accelerate toy handling skills (van den Berg & Gredebäck, 2021). This suggests that sensorimotor experience helps infants anticipate caregivers' actions. Also, there is naturalistic evidence that mothers actively scaffold infants' attention to, and exploration of, object affordances (Zukow-Goldring & Arbib, 2007), further suggesting that social input affects motor skill development. The current study focuses on a related question, extending de Barbaro et al.'s (2016) results: are individual sensorimotor decoupling trajectories from 4 to 12 months related to mothers' object-related actions?

If infant sensorimotor decoupling is contingent on caregivers' toy handling actions, it might imply that decoupling matures in part through triadic interactions, and that caregiver triadic object manipulation patterns can scaffold the development of decoupling skills. A strong contingency between infant decoupling and maternal object manipulation would suggest that infants' attention is diverted to objects attended by the mother. Such evidence would support de Barbaro et al.’s suggestion that decoupling helps infants transition from dyadic to triadic interactions (2015).

1.4. Attention Decoupling and Early Motor Development

Infant motor development has been associated with dyadic coordinated attention (Johnson, 2010). From 4 to 9 months infants increasingly manipulate objects, and they increasingly share attention with caregivers. Thus, motor development might facilitate triadic engagement, and vice versa. For example, from 4.5 to 7.5 months infants increasingly sit unsupported, which improves control over manual and visual attention to objects (Soska, Adolph & Johnson, 2010).

Given these patterns, we would predict individual differences in the trajectory of decoupling to be associated with general motor maturation (e.g., Darrah, Redfern, Maguire, Beaulne, & Watt, 1998). To test this prediction we used infants' motor scores from the age-normed Bayley Scales of Infant Development (BSID-III: Bayley, 2006; Nellis & Gridley, 1994) – specifically, the fine and gross motor subscales, which show moderate reliability and validity (e.g., Hoskens, Klingels, & Smits-Engelsman, 2018). We hypothesized that infants' decoupling might predict their later motor development. We also examined whether infants' decoupling was associated with their age of attaining key motor milestones, based on a monthly parent questionnaire. We hypothesized that infants with earlier-developing motor skills will show accelerated decoupling.

1.5. Attention Decoupling and Early Communication Skills

We also examined whether earlier decoupling predicted infants' later communication skills. Previous evidence suggests that both fine and gross motor development modestly predict infant language development (LeBarton & Iverson, 2013; Walle & Campos, 2014) and that engagement in joint attention and triadic interactions also predicts later language skills (Tomasello & Todd, 1983; Moore, 2013). We used the BSID-III communication composite scores (i.e., receptive and expressive subscales), administered at 18 months, to estimate infants' early language skills. BSID scores show moderate predictive validity for both low- and high-risk children (Goldstein et al., 1995; Lung et al., 2009). We hypothesized that these scores would be correlated with infants' decoupling, especially decoupling contingent on mothers' actions.

1.6. Classification of Trajectories of Decoupling Development

Additionally, de Barbaro et al. (2016) classified infants' decoupling maturity based on a median split of their Gaze-Hand decoupling at 6 months to investigate whether differences in decoupling rates were related to their responses to maternal object bids. De Barbaro et al. found that Low decouplers responded to maternal object bids like younger infants, whereas High decouplers responded like older infants. Here we characterize infants' decoupling trajectory more broadly, defining High and Low decouplers based on each type of decoupling -- Gaze-Hands and Hand-Hand -- at three ages: 4, 6, and 9 months[1]. This should increase the reliability of any stable individual differences, for a more generalizable classification of individual infants.

Moreover, in de Barbaro et al. (2016) the factors contributing to differences in decoupling rates were unclear. We explore whether subgroups of decoupling patterns are correlated with other developing motor and social skills. Because infants around the middle of the first year vary widely in motor and social skills (Ruff & Dubiner, 1987; Liszkowski & Tomasello, 2011), we consider whether individual differences in motor and communication skills could be moderated by trajectories of decoupling development.

In summary, we hypothesized, first, that the development of infant sensorimotor decoupling is related to caregivers' actions in triadic interactions – i.e., socially-contingent decoupling. Second, we hypothesized that longitudinal differences in decoupling are related to

[1] Longitudinal clustering (Genolini, 2016) was used to capture decoupling rates across all three ages, and the resulting trajectories.

infants’ motor and social-communicative skills. Third, we hypothesized that unsupervised clustering of longitudinal decoupling data across 4, 6, and 9 months will yield more holistic, data-driven High- and Low-Decoupling groups than a median-split on one kind of decoupling at one time point.[2] Fourth, we hypothesized that individual trajectories of Gaze-Hand and Hand-Hand decoupling from 4 to 9 months will be correlated.

2. Methods

2.1. Participants

Forty-two mother-infant dyads were enrolled in a longitudinal study of infant social development (see Chang & Deak, 2019). This sample of convenience was recruited from the greater San Diego area. Four participants were excluded from analysis due to equipment failure or for use of non-English speech[3], resulting in a sample of 38 dyads. Mothers’ mean age at recruitment (when infants were 3 months old) was 32.1 years (range = 21-42), with an average of 16.1 years of education (range = 12-21). Parents' reported that 29 infants were Caucasian, four were Hispanic, two were Asian, and five were “other” or multiracial. Two parents provided no race/ethnicity information. No infants had parent-reported neurological, cognitive, or sensory deficits.

2.2. Materials

2.2.1 Testing environment.

Dyads were recorded in their homes. Infants sat in an immobilized walker with a tray, facing their mother who sat on a pillow on the floor. Three Canon mini-DV video cameras

[2] Because our sample was North American, English-using predominantly-"WEIRD" (i.e., White, Educated, Industrialized, Rich, and Democratic; Heinrich, Heine, & Norenzayan, 2010) families, all hypotheses and interpretations pertain only to that population, and are not presumed to generalize to other populations.
[3] Because other analyses of this corpus focus on language data.

recorded, respectively, (1) the infant's head and upper body and the tray; (2) the mother's head and upper body and the tray; and (3) the dyad in zoomed-out profile view (Figure 1).

2.2.2. Toys.

Toys were placed on the tray or in holders mounted on each side of the tray. Toy sets each month included one toy that made sounds, one toy with a face, and a third age-appropriate toy. At 4 months they included a baby toy with sound-producing buttons, a round-bottomed wobbling animal, and a plastic caterpillar (Figure 2a). At 6 months they included a plastic toy with sound-producing rattles, a different wobbling animal, and a foam soccer ball (Figure 2b). At 9 months they included a different rattle, a third wobbling animal, and an American football. (Figure 2c).

Figure 1

Frame From Home Toy-Play Interaction

Note: Synchronized composite frames (de-identified) from digitally captured videos from three cameras. Left: mother-focused camera view; Right top: contextual view; Right bottom: infant-focused view. Coders could resize windows to optimize accuracy.

Figure 2

Toys Provided At Each Session

Note: A: 4-months toys; B: 6-month toys; C: 9-month toys.

2.2.3 Procedure.

Toy play sessions took place in families' homes, and preceded another interaction not analyzed here. Average session duration was 267.3 seconds at 4 months (range = 167s - 450s), 321.1 at 6 months (242s - 505s), and 333.8 at 9 months (186s - 589s).

Infants' and mothers' toy-handling actions, and infants' gaze fixations during each session, were coded, using all three videos (synchronized, at 10 frames/sec), by randomly assigned, trained coders, using ELAN (http://www.lat-mpi.eu/tools/elan/). Files were checked for accuracy and completeness by an experienced staff researcher or graduate student.

Infant gaze fixation coding. Trained coders annotated each infant gaze fixation (with onset and offset times) to a toy or toys, the mother, or other objects.

Toy-handling activity coding. Trained coders annotated all toy handling events for both mothers and infants, including onset and offset times and the identities of toys being handled

Intercoder reliability. Sessions were quasi-randomly selected from each month and independently transcribed by a second coder. 33% of the sample was re-coded for infant hands, 37% for mother hands, and 33% for infant gaze. Kappas (Cohen, 1968) averaged 0.85 for infant handling, 0.92 for mother handling, and 0.79 for infant gaze (Chang & Deak, 2019).

2.3 Data coding

2.3.1 Manual actions

Mother toy-handling actions. Mothers' toy-handling actions were categorized as pick-ups, touches, or drops. A *pick-up* occurred when the mother touched a toy that was not touched in the previous frame. A *touch* occurred when the mother was in physical contact with a toy for >=2 consecutive frames. A *drop* occurred when the mother stopped touching a toy that was touched in the previous frame.[4]

Infant toy-handling l actions. We recorded the onset and offset times when an infant's left or right hand made contact with any toy.

2.3.2 Decoupling.

Infant Gaze-Hand decoupling rate. Gaze-Hand (G-H) decoupling was coded when the infant’s gaze and hands were directed to different objects. Gaze-Hand decoupling rate was calculated as the number of frames in which the infant looked at one target while touching at least one different toy, divided by the total frames when the infant was touching any toy. (Because infants virtually always look at *something*, it is only sensible to use *touching* frames as the denominator.) However, there is a dependency between H-H and G-H decoupling: when the infant

[4] The results do not change if touching events are thresholded with a 1 sec minimum, as in de Barbaro et al. (2012).

simultaneously holds two objects, they typically focus gaze on only one object. Therefore, we only considered G-H decoupling that did not occur during Hand-Hand decoupling. Eighteen percent of G-H decoupling occurred during H-H decoupling and was excluded from these analyses.

Infant Hand-Hand decoupling rate. Hand-Hand (H-H) decoupling occurred when the infant's hands contacted two different toys. Rate was calculated as the number of frames when the infant's hands touched different objects, divided by the total frames when the infant was touching any toy.

2.3.3 Social behaviors

Infant Contingent decoupling rate. Infant decoupling rates contingent on mothers' toy-handling actions were calculated as the number of frames of decoupling that occurred within 5 sec after a mother picked up or dropped a toy that the infant explored in the decoupling event, divided by the total frames when the infant was touching any toy.

BSID scaled data. Infants completed the BSID-III (Bayley, 2006), a standardized test of developmental status, at 12 and 18 months of age. It includes brief, age-normed behavioral and parent-report items, with subscales to estimate developmental status in cognitive, motor, communication, and social-emotional areas. As a proxy of communicative skills we consider scaled composite scores from the expressive and receptive communication subscales. Outliers (defined by z-transformed scores > |2.5| *SD* from the mean) were winsorized to 2.5 *SD*.

2.3.4 Motor development.

Motor milestone data. A Motor Development Milestones Questionnaire (MDMQ; Supplementary materials) developed in our lab tracked each infant's age of acquiring specific motor skills. At each monthly visit mothers indicated, to the nearest week, when their infant first displayed a new skill. Experimenters described and showed photographs of each behavior in a laminated booklet, to ensure parents' understanding. To test the relation between decoupling and motor development we calculated the infant's average age of all motor milestones, with lower averages reflecting faster maturation . We also calculated each infant's mean age of earlier and later milestones, based on a median split of the median ages for each milestone.

In addition, the normed, scaled composite scores from the fine and gross motor subscales of the BSID were used as standardized tests of overall motor development.

2.3.5 Statistical analysis.

Data were analyzed using RStudio (v4.0.3; 2013) and the Python 3 packages Pandas, Numpy, Pingouin, Sklearn and Scikit (see pypi.org).

K-means longitudinal clustering. The R Package KmlShape (Genolini, 2016) was used to divide subjects into a *High decoupling* and a *Low decoupling* group cluster, based on their longitudinal trajectories of decoupling rates (H-H and G-H) across 4, 6, and 9 months. The clusters were initiated by randomly selecting two trajectories. The centroid of each cluster was calculated as the average of all trajectories in the cluster, and each subject was assigned to the cluster with the nearest centroid. Each centroid was updated with each new data point. The clusters were finalized when the last data point did not change the value of the centroid, or when the maximum interaction was reached.

Post hoc tests and repeated measures ANOVA (rmANOVA) with Bonferroni-corrected paired sample t-tests were performed for pairwise multiple comparisons to assess individual differences in decoupling rates across months. Analyses of covariance (ANCOVAs) were performed to test for differences in G-H and H-H decoupling rates in High and Low decoupling groups. Partial correlation tests were performed to assess relations between overall or contingent decoupling rates, and BSID-III composite motor and language scores, controlling for covariates such as maternal education. Repeated-measures correlations (RM-correlation, or rmcorr) were conducted to assess within-subject, across-month correlation between G-H and H-H decoupling, and between overall and contingent decoupling. The rmcorr analysis of variance (ANOVA) function accounts for between-subject variance and represents the linear relationship between two measures as parallel lines with the same correlation coefficient, and different intercepts for each individual (Bakdash & Marusich, 2017); see Figures 12-13. Infants with 0-1 manual actions per session were excluded from analysis, leaving n=42 dyads with complete data in months 4, 6, and 9 for rmcorr analyses. H-H and G-H decoupling data were winsorized to 2.5 *SD*s, affecting fewer than 5% of data points. The data and analysis codes are available at: https://osf.io/bnyhk/.

3. Results

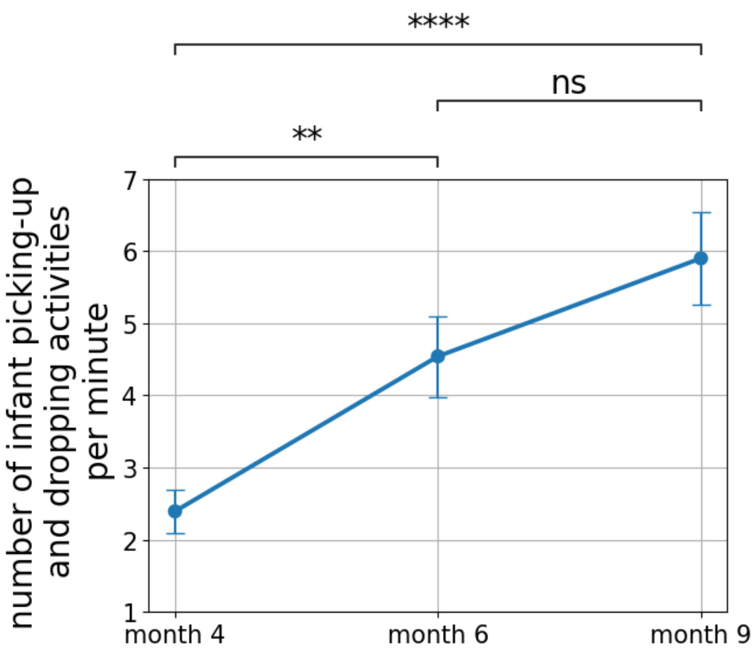
3.1. Infant intermodal activity rate increases from 4 to 9 months

3.1.1 Infant toy handling rate.

Infant toy handling rate (Figure 3) was the number of times per minute the infant picked up or dropped an object. A rmANOVA test shows a significant age effect, $F(2, 125) = 12.06$, $p < 0.0001$. Post-hoc tests show significant increases from 4 months ($X = 2.14$, SD = 1.80) to 6 months (4.31, $SD = 3.27$), $p = 0.0038$; and from 4 to 9 months (5.45, $SD = 3.95$), $p < 0.0001$. The difference between 6 and 9 months, however, was not significant ($p = 0.36$).

Figure 3

Mean Rate of Infant Toy-Handling, By Age



Note. Y-axis: mean numbers (per min) of infant toy-handling actions (i.e., total picking-up and dropping events) per session. Error bars = SE_{mean}. ** $p < .01$; **** $p < .0001$.

3.1.2 Infant visual fixation rate

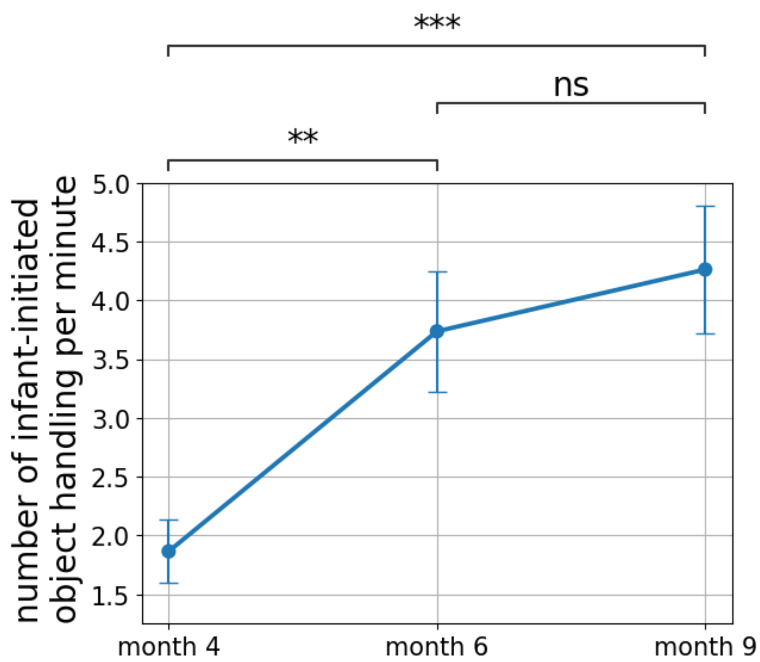
Infant visual fixation rate was the infant's rate (per min) of discrete fixations of either toys, or the mother. A rmANOVA shows that there was not a significant difference across age ($F(2, 125) = 0.785$, p = 0.46).

3.1.3 Infant-initiated toy handling rate

Infant-initiated toy handling rate (Figure 4) was the infant's rate (per min) of picking up toys that neither participant had touched within the last 5.0 sec. A rmANOVA shows a significant age difference across months $F(2, 125) = 8.99$, $p < 0.001$. Post-hoc tests show a significant increase from 4 ($X = 1.60$, $SD = 1.48$) to 6 months (3.53, $SD = 2.96$), $p = 0.006$; and from 4 to 9 months (3.96, $SD = 3.34$), $p < 0.001$; but not from 6 to 9 months ($p > .5$).

Figure 4

Mean Rate of Infant-Initiated Toy Handling Events, By Age



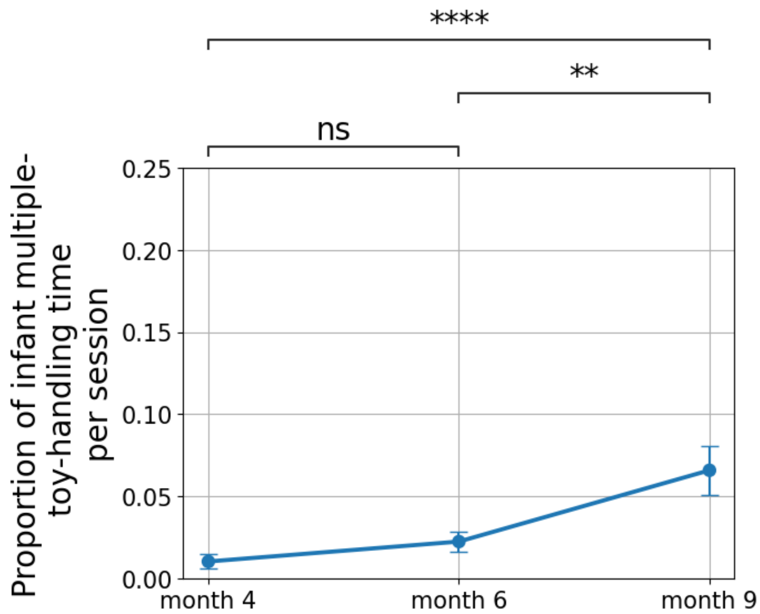
Note. Y-axis: mean rates (per min) of infant-initiated toy handling actions per session. Error bars = SE_{mean}. ** $p < .01$; *** $p < .001$.

3.1.4 Infant multiple-toy handling rate

Infant multiple-toy handling rate (Figure 5) was calculated as the proportion of time (i.e., frames, at 10Hz) when infants simultaneously touched two toys with their hands, divided by the session duration (minus un-codable intervals). A rmANOVA shows a significant age effect in multiple-toy handling, $F(2, 125) = 8.63$, $p < 0.001$. Post-hoc test shows reliable increases from 4 ($X = 0.01$, $SD = 0.03$) to 9 months (0.07, 0.10), $p = 0.003$; and from 6 (0.04, 0.02) to 9 months, $p < 0.05$, but not from 4 to 6 months ($p = 0.12$).

Figure 5

Mean Proportion of Infant Multiple-Toy-Handing Time, By Age



Note. Means of infant multiple-toy-handling time out of total coded time per session. Error bars = SE_{mean}. * $p< .05$; *** $p< .001$.

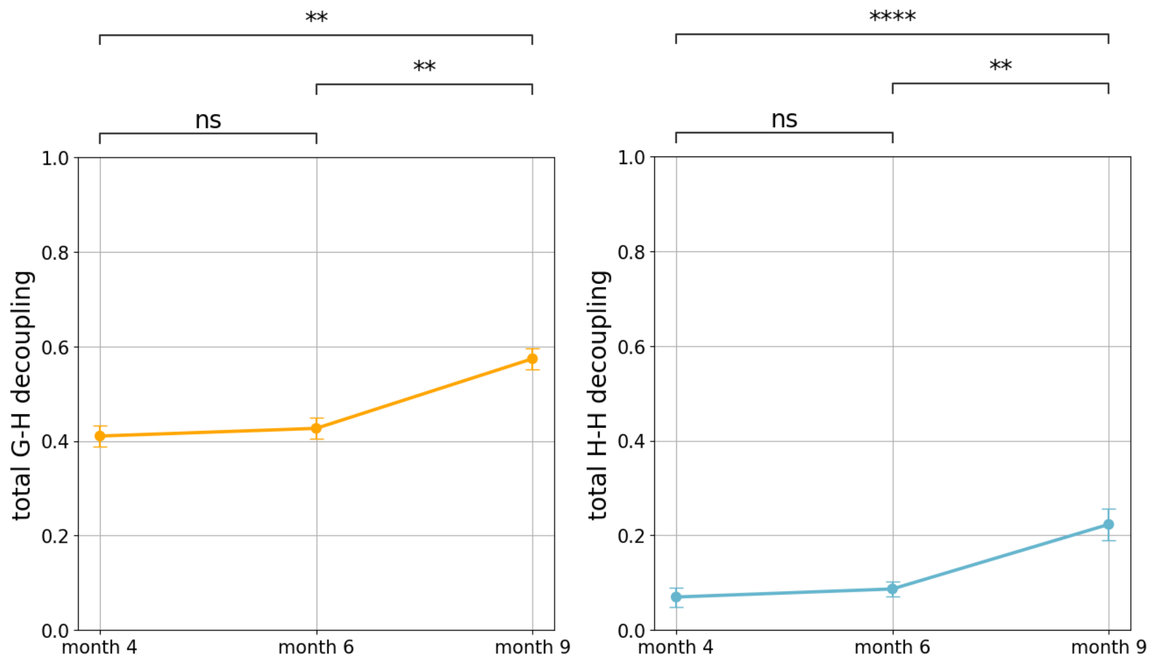
3.2. Gaze-Hand and Hand-Hand decoupling increases with age

3.2.1 Gaze-Hand decoupling

A rmANOVA shows a significant age effect in proportion of Gaze-Hand decoupling (Figure 6, left), $F(2, 78) = 7.85$, $p < 0.001$. Post-hoc tests show a significant increase from 4 (X = 0.41, SD = 0.28) to 9 months (0.57, 0.17), p =0.009; and from 6 (0.42, 0.19) to 9 months, p = 0.002; but not from 4 to 6 months (p > .5).

Figure 6

Mean Proportion of Infant Gaze-Hand and Hand-Hand Decoupling Time, By Age



Note: Left: Means of Gaze-Hand decoupling time, out of total coded time per session. (Note that rates exclude 18% of G-H decoupling time during H-H decoupling.) Right: Means of Hand-Hand decoupling time. Error bars = SE_{mean}. ** $p < .01$. *** $p < .001$.

3.2.2 Hand-Hand decoupling

A rmANOVA shows a significant age effect in Hand-Hand decoupling (Figure 6, right), $F(2, 78) = 12.09$, $p < 0.001$. Post-hoc tests show a significant increase from 4 ($X = 0.062$, $SD = 0.12$) to 9 months (0.22, 0.21), $p < 0.001$; and from 6 (0.079, 0.097) to 9 months, $p < 0.01$; but not from 4 to 6 months ($p > .5$).

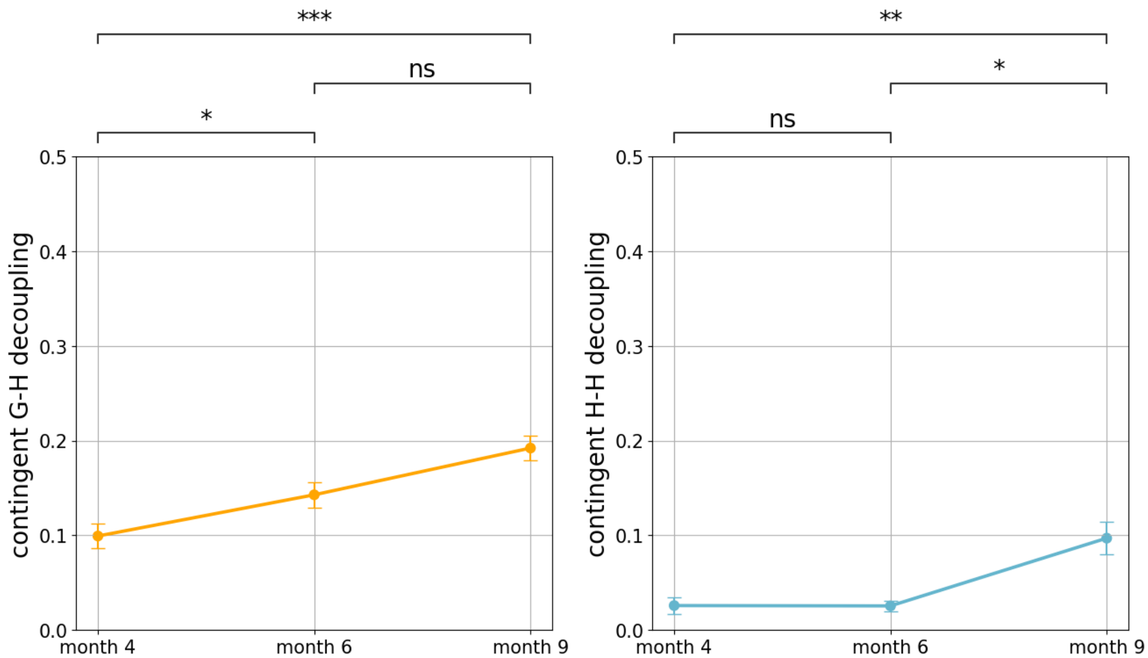
3.3. Development of decoupling contingent on maternal action increases with age

3.3.1 Contingent Gaze-Hand decoupling

A rmANOVA shows a significant age effect in the proportion of Gaze-Hand decoupling contingent on maternal toy-handling actions (Figure 7, left), $F(2, 78) = 7.06$, $p = 0.002$. Post-hoc tests show significant increases from 4 (X = 0.10, SD = 0.15) to 9 months (0.19, 0.12), p = 0.011; but not from 4 to 6 months (0.14, = 0.11), p = 0.46; nor from 6 to 9 months (p = 0.23).

Figure 7

Mean Proportion Infant Contingent Gaze-Hand and Hand-Hand Decoupling Time, By Age

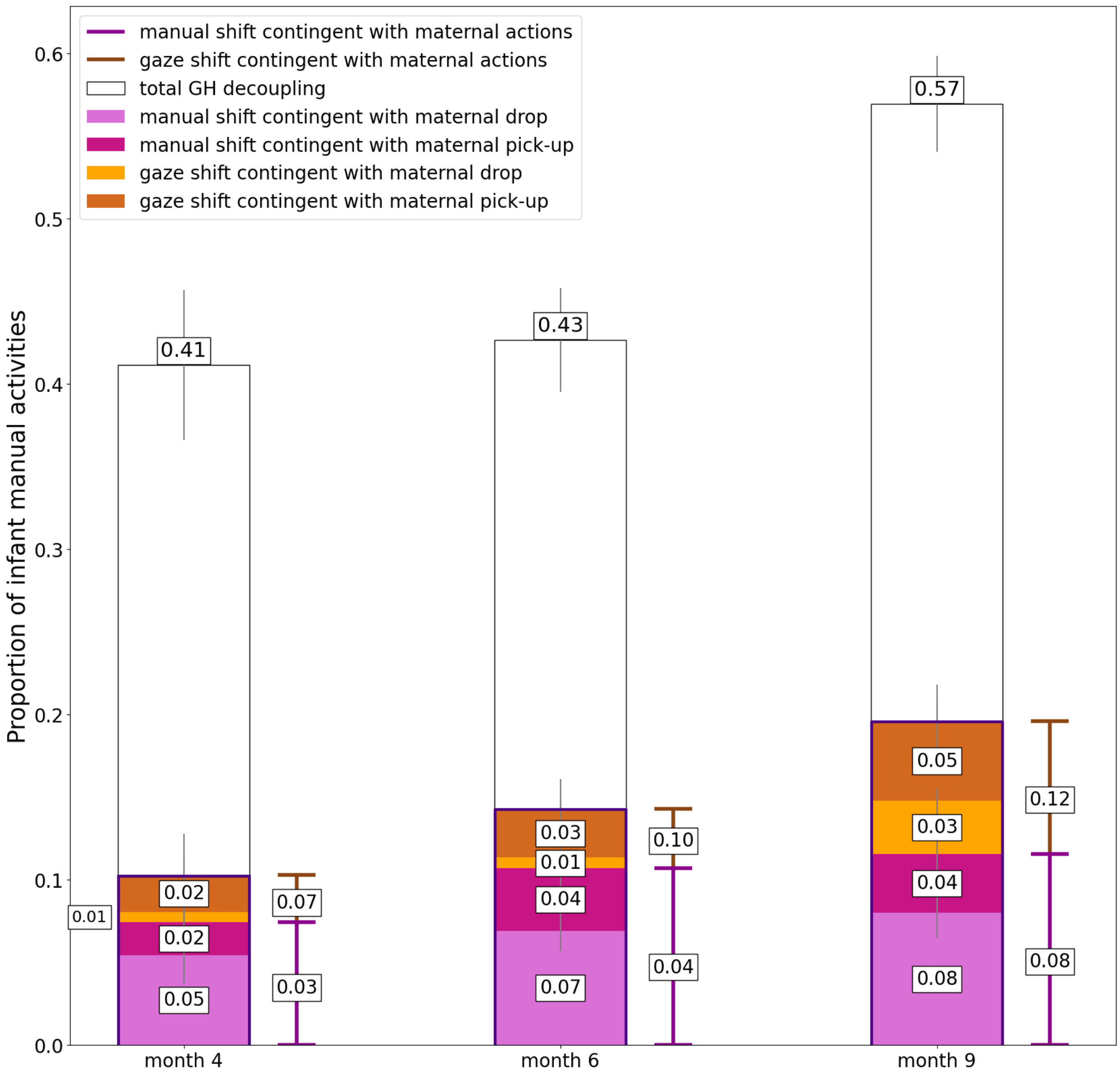


Note: Left: Mean proportions of contingent Gaze-Hand decoupling time (out of total coded time per session; note that the scale is less than in Fig. 6). Right: Mean proportions of contingent Hand-Hand decoupling time. Error bars = SE_{mean} . * p < .05; ** p < .01; *** p < .001.

Figure 8 shows the proportion of infant G-H decoupled time, out of total infant toy handling time. Each bar with a black outline represents the mean total G-H decoupling rate in a given month. The purple outline within each bar shows the mean contingent G-H decoupling rate. *Contingent manual shifts* and *contingent gaze shifts* are subsets of events when the infant shifted their hand or gaze, respectively, during a decoupling event, to attend to a toy manipulated by the mother. The colored portions of each bar represent rates of specific types of infant contingent G-H decoupling - i.e., events initiated by a shift of either infant's gaze (orange segments) or hand(s) (pink segments), contingent on maternal manual actions. Within those segments, events are further divided into lighter or darker segments to indicate rates of switches contingent on a maternal pick-up (darker segment) or dropping action (lighter). The I-bar line segments at the right of each bar indicate the mean rates of contingent decoupling that began with the infant's gaze shifts (brown segment), or hand shifts (purple segment).

Figure 8

Proportions of Infant G-H Decoupling Types, Overall And Relative To Maternal Manual Action



Note. Proportions of infant G-H decoupling activities out of all infant toy-handling actions. See text for explanation.

Overall infant G-H decoupling showed no reliable difference in contingency to mother dropping vs. picking-up events at any age: at months 4 (contingent on drops: *X* = 0.43, *SD* = 0.44; on pick-ups: 0.22, 0.35), or at 6 months (drops: 0.47, 0.38; pick-ups: 0.37, 0.36), or at 9 months (drops: 0.53, 0.33; pick-ups: 0.42, 0.32). Note that although maternal drops and pick-ups must be roughly equal in frequency, infants need not be equally attentive to both actions.

However, further analyses show that infants did not redirect gaze and hands equally in response to mothers' object actions. When they decoupled by shifting gaze to a mother-handled object, they shifted more to picked-up than dropped objects: at 4 months (picked-up: $X = 0.022$, $SD = 0.011$; dropped: 0.006, 0.004); at 6 months (picked-up: 0.029, 0.007; dropped: 0.006, 0.003); and at 9 months (picked-up: 0.048, 0.012; dropped: 0.031, 0.007).

By contrast, when infants decoupled by shifting *hands* to a mother-handled object, they shifted *more* to dropped than to picked-up objects: at 4 months (dropped: $X = 0.055$, $SD = 0.017$; picked-up: 0.020, 0.007); at 6 months (dropped: 0.069, 0.012; picked-up: 0.038, 0.013); and at 9 months (dropped: 0.080, 0.015; picked-up: 0.035, 0.010). Thus, infants decoupl both gaze and manual in response to mothers' toy-handling, but were more likely (or faster) to shift gaze when mothers picked up an object, and more likely to shift *hands* when mothers *dropped* an object.

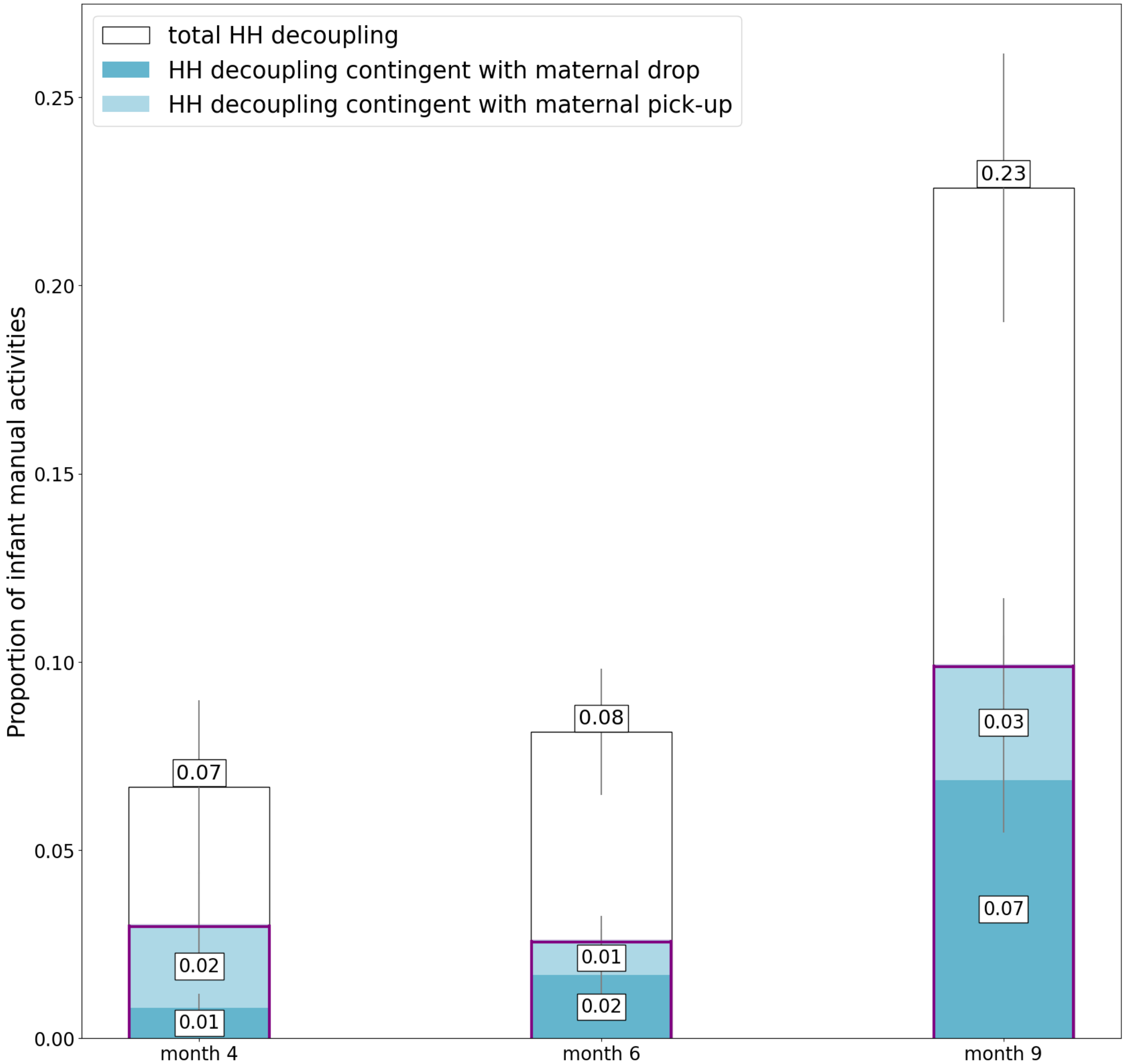
3.3.2 Contingent Hand-Hand decoupling

A rmANOVA shows a significant age effect in the proportion of Hand-Hand decoupling contingent on mothers' manual actions (Figure 7, right), $F(2, 78) = 11.27$, $p < 0.001$. Post-hoc tests show a significant increase from 4 ($X = 0.029$, $SD = 0.064$) to 9 months (0.12, 0.13), $p = 0.001$; and from 6 (0.041, 0.057) to 9 months, $p < 0.001$; but not from 4 to 6 months ($p > .5$).

Figure 9 shows the proportion of infant H-H decoupled time out of all infant toy-handling time. Bars with black outlines represent total H-H decoupling, and the purple outlined portions show contingent H-H decoupling rates. Colored stacked bars show infant H-H decoupling rates contingent on maternal toy-handling actions: picking-up or dropping.

Figure 9

Proportions of Infant H-H Decoupling: Overall And Relative To Maternal Toy-Handling



Note. Proportion of infant H-H decoupling, out of all frames with infant manual object-actions.

With age, infants increasingly decoupled hands by grasping an object dropped by their mother: at 4 months (to drops: X = 0.008, SD = 0.004; to pick-ups: 0.022, 0.014); at 6 months (drops: 0.016, 0.005; pick-ups: 0.009, 0.003); and at 9 months (drops: 0.069, 0.014; pick-ups: 0.031, 0.008).

3.4. Decoupling developmental differences are correlated with developing motor skills.

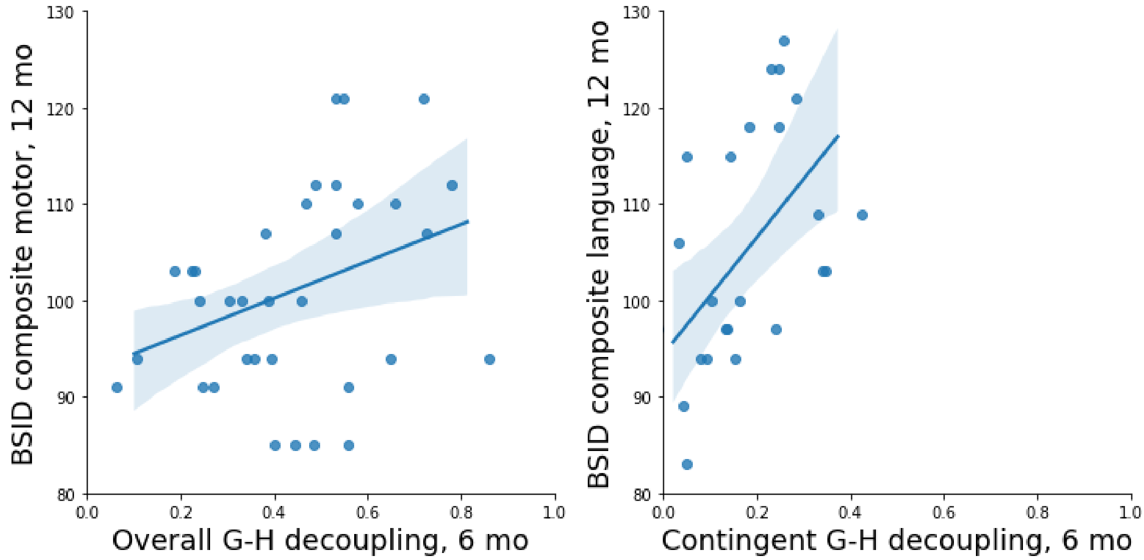
Infant decoupling skills at 6 months are correlated with motor skills at 12 months. Partial Spearman correlations, controlling for maternal education[5], show significant positive associations between G-H decoupling rate at 6 months ($r_p = 0.35$, $p = 0.045$), and BSID composite motor scores at 12 months ($X = 100.61$, $SD = 10.46$; Figure 10, left). Furthermore, infant decoupling is correlated with both fine and gross motor skills (see Supplementary Materials), with a significant partial correlation (controlling for maternal education) between scaled fine motor scores at 12 months ($X = 9.59$, $SD = 2.17$) and G-H decoupling at 6 months ($r_p = 0.35$, $p = 0.033$), and a significant partial point biserial correlation (controlling for maternal speech quantity and maternal education) between scaled gross motor score at 12 months ($X = 10.96$, $SD = 2.50$) and contingent H-H decoupling at 9 months ($r_p = 0.37$, $p = 0.047$). There were no other reliable correlations between G-H or H-H decoupling, and BSID motor scores.

We also tested correlations between infant decoupling and infant motor milestones, but found no significant relations. This was also true for only the later-acquired milestones.

Figure 10

Correlation Between Decoupling Rates and BSID Motor Score

[5]Maternal education has been associated with infant motor development (Chase et al., 2000; Jassen et al., 2008).



Notes. Left: Regression line and scatter plot relating Gaze-Hand decoupling rate at 6 months to BSID composite motor scores at 12 months. Right: Regression line and scatter plot relating Gaze-Hand decoupling rate at 6 months to BSID composite language scores at 18 months.

3.5. Decoupling changes are correlated with developing communication skills.

To evaluate whether individual decoupling predicted later communication skills, we examined associations with BSID-III composite communication scores at 18 months (see Supplementary Materials). There was a significant Spearman correlation, controlling for maternal education, between contingent G-H decoupling at 6 months and composite scores (X = 103.88, *SD* = 12.97; r_p = 0.43, *p* =0.037); see Figure 10 (right). However, G-H and H-H decoupling (overall or contingent) were not significantly related to composite communication scores or their subscales (receptive; expressive) in other months.

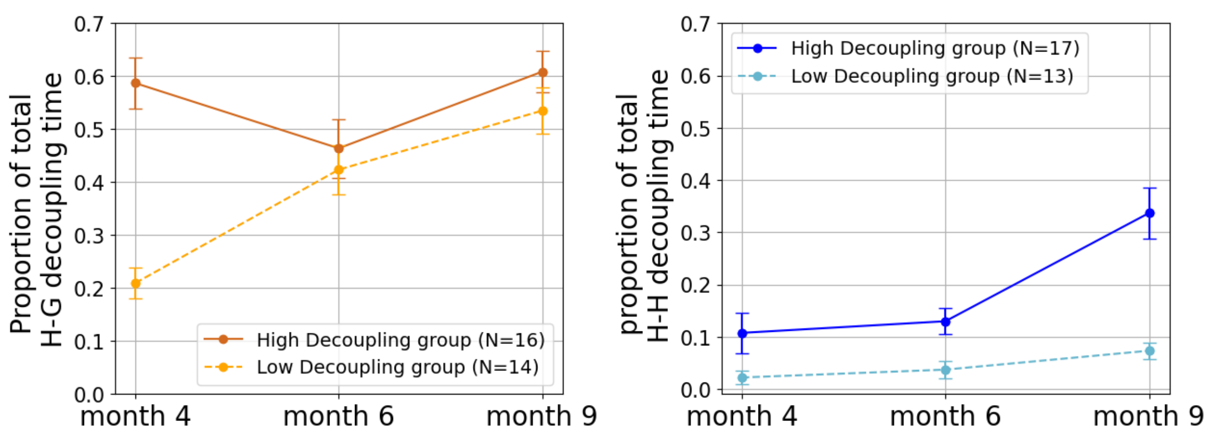
3.6. Longitudinal classification of High and Low Decoupling infants

Based on longitudinal data, KmlShape classified infants into Low and High G-H Decoupling groups. G-H decoupling increased from 4 to 9 months in the Low group, but the high group remained relatively high and stable across months. The Low and High groups differ reliably in G-H decoupling at 4 months (one-way ANCOVA, covarying maternal education): $F(1, 27) = 40.07$, $p < 0.001$. However, they did not differ reliably at 6 months ($F(1, 27) = 0.28$, $p = 0.60$) or at 9 months ($F(1, 29) = 1.45$, $p = 0.23$); see Figure 11 (left).

By contrast, for both H-H groups, decoupling increased from 4 to 9 months. Furthermore, a one-way ANCOVA (covarying education) shows a marginal Low vs. High H-H decoupling difference at 4 months, $F(1, 29) = 4.18$, $p = 0.051$, and significant differences at 6 months, $F(1, 27) = 9.94$, $p < 0.01$, and at 9 months, $F(1, 27) = 19.28$, $p < 0.001$ (Figure 11, right).

Figure 11

Proportions of G-H and H-H Decoupling By High- and Low-Decoupling Groups, By Age



Note. Left: Low (dashed orange line), and High (solid brown) G-H Decoupling groups' mean proportions of G-H decoupling time, out of total coded time per session. Error bar = SE_{mean}.. Right: Low (dashed cyan line) and High (solid blue) H-H Decoupling groups' mean proportion of H-H decoupling.

3.7. Correlation between G-H and H-H decoupling

To explore the relation between the development of infant G-H and H-H decoupling, we calculated Pearson correlations between overall G-H and H-H decoupling rates, and between contingent G-H and H-H decoupling rates. There was a significant positive correlation between contingent G-H and H-H decoupling at 9 months (r = 0.36, p < 0.05). However, there were no other significant associations between metrics of G-H and H-H decoupling, at any age.

We then used RM-correlation to assess paired within-subject, across-month correlations between G-H and H-H decoupling, and between overall and contingent decoupling. The analysis of variance (ANOVA) function in rmcorr accounts for between-subject variance and represents the linear relation between two measures as parallel lines with a single correlation coefficient, with different intercepts for each individual.

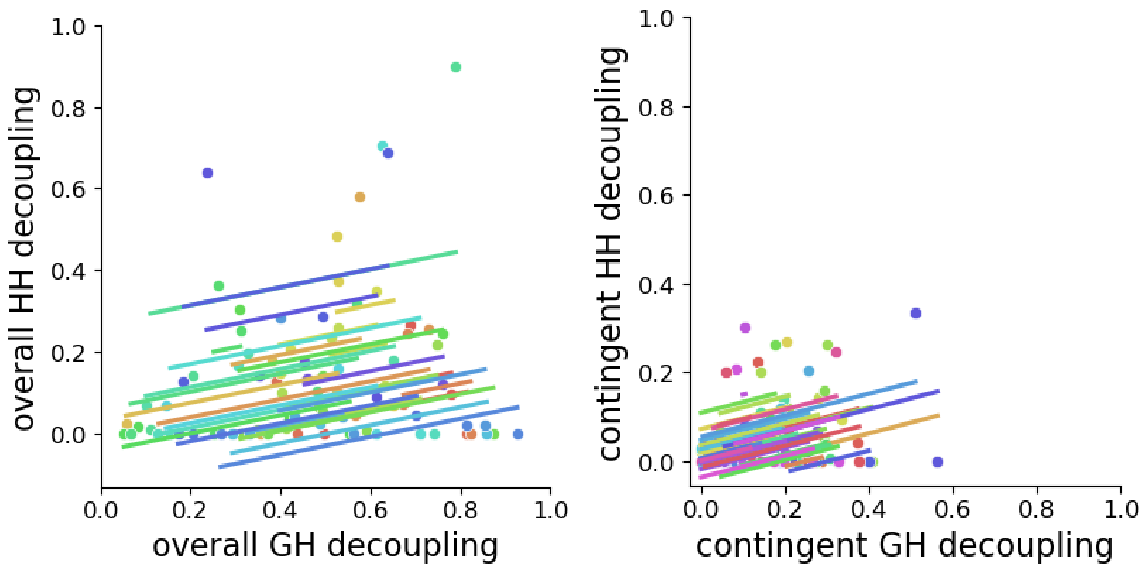
First, rmcorrs (N=30)[6] show a significant but modest positive correlation between total G-H and H-H decoupling rates ($r_{rm}(df{=}59)$ = 0.28, p < 0.05; Figure 12, left).

Second, individual infants' contingent G-H and H-H decoupling trajectories showed significant but modest positive rmcorrs (N=30) across months 4, 6, and 9 ($r_{rm}(59)$ = 0.36, p < 0.01; Figure 12, right). However, it is unclear how sensorimotor maturation, mothers' object-manipulation, or other factors contributed to this association.

Figure 12

Repeated-Measures Correlations Between G-H and H-H Decoupling: Overall and Contingent

[6] Due to missing data, 7 to 12 infants were excluded per analysis.

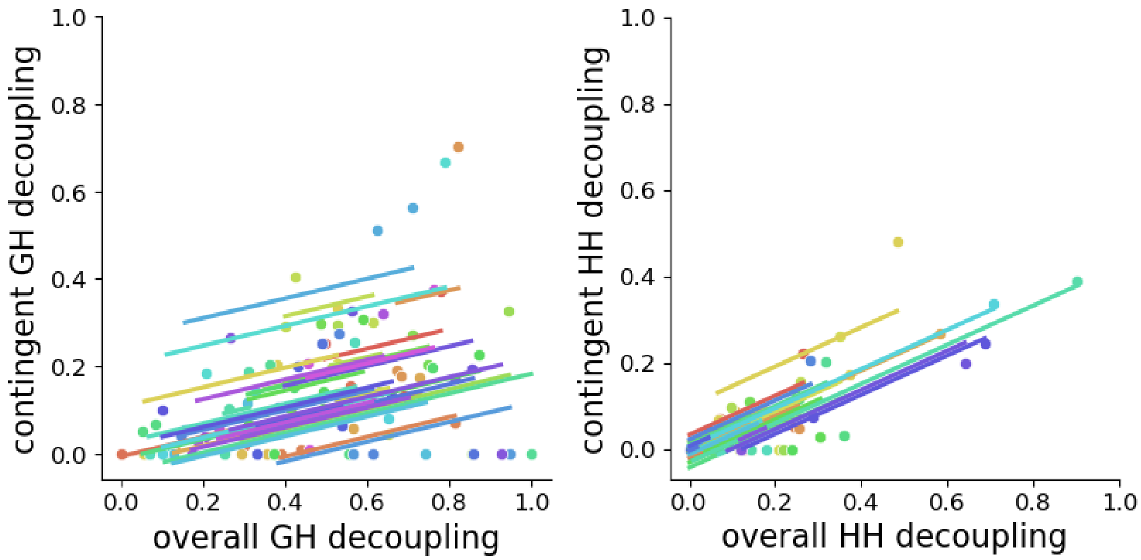


Note. Left: RM-correlations between overall G-H and H-H decoupling rates across 4, 6, and 9 months. Each line is an infant's linear regression across sessions (each session is a point). Lines and points of a given color reflect data from one infant. Right: RM-correlations between contingent G-H and H-H decoupling across 4, 6, and 9 months.

To address whether G-H decoupling is driven by changes in infants' sensorimotor maturation, versus facilitation by maternal action, we examined RM-correlations (N=35) between overall G-H decoupling and contingent G-H decoupling. There was a significant positive correlation across 4, 6, and 9 months ($r_{rm}(69) = 0.41$, $p < 0.001$; Figure 13, left). Although significant, it shows that only a modest proportion of variance in individuals' G-H decoupling trajectories is predicted by their rate of *contingent* decoupling.

Figure 13

Repeated-Measures Correlations Between Overall and Contingent Decoupling Rates



Note. Left: RM-correlations between overall and contingent G-H decoupling rates across 4, 6, and 9 months. Lines and points are as described in Figure 13. Right: RM-correlations between overall and contingent H-H decoupling rates across 4, 6, and 9 months.

Another RM-correlation tested whether the trajectory of H-H decoupling was driven by responses to maternal actions. This rmcorr (*N*=31) shows a significant positive correlation between trajectories of total H-H and contingent H-H decoupling across 4, 6, and 9 months ($r_{rm}(61) = 0.85$, $p < 0.001$; Figure 13, right). Unlike the G-H rmcorr above, this relation is robust, suggesting that infants' contingent responses to maternal action (especially putting down objects) provide opportunities for infants to practice and develop manual decoupling skills.

4. Discussion

We examined infant gaze and manual shifting events at 4, 6, and 9 months, and confirmed and extended findings that across this age span infants increasingly distribute their sensorimotor attention across different objects. That is, infant gaze-hand (G-H) and hand-hand (H-H) decoupling rates increase from 4 to 9 months. We also examined whether decoupling was related to specific events during triadic interactions. For this we analyzed how G-H and H-H decoupling was contingent on mothers' toy-handling actions - notably, picking up or putting down toys. We showed that infants increasingly and selectively decoupled based on mothers' toy-handling actions.

We also examined whether infant G-H and H-H decoupling was associated with infant motor skills, via partial correlations with BSID-III fine, gross, and composite motor scores. Analogously, we examined whether *contingent* decoupling predicted later communication skills, via partial correlations with BSID-III communication composite scores. Finally, to characterize individual differences in decoupling development, we modeled subgroups of infants with Low vs. High decoupling trajectories, for both G-H and H-H decoupling, using longitudinal k-means clustering. These analyses make the current study one of few to investigate associations between fine-grained caregiver action and longitudinal trajectories of specific infant triadic skills.

4.1. From 4 To 9 Months Infants Increasingly Shift Visual And Haptic Attention

Our results are consistent with previous evidence (Berthier & Carrico, 2010; Pereira et al., 2014; Corbetta et al., 2018) that from 4 to 9 months infants increasingly control and decouple their visual and manual activities, and more fluidly shift visual and haptic attention. As infants got older they picked up and dropped objects more often, initiated toy handling more often, and simultaneously touched and/or looked at multiple objects more often. This suggests developing sensorimotor skills to multimodally distribute and re-focus their attention among multiple targets (de Barbaro, 2016). Our results also support findings that with increasing age, infants' visual attention is less dominated by caregivers' actions (e.g., Burling & Yoshida, 2018): from 4 to 9 months infants increasingly shifted attention to objects recently dropped by their mother. This suggests that infants' attention becomes less determined by caregivers' current focus of attention, even as they become more sensitive to action-opportunities afforded by caregivers' actions.

Infants' increasing decoupling of gaze and hands was reported by de Barbaro et al. (2016). Notably, mean G-H decoupling at 9 months exceeded 0.55: that is, when infants were touching a toy, over half of the time they were looking at another object. Often they were visually monitoring their mother's actions, and/or to an object that they were preparing to grasp. This suggests that infants' growing ability to distribute sensorimotor modalities might contribute to future-oriented cognition (e.g., Morrongiello & Rocca, 1989), including planful engagement in social interactions. Note also that *total* G-H decoupling from 4 to 9 months was higher than the rates reported here, because we excluded 18% of G-H decoupling that occurred during H-H decoupling.

4.2. Infants Contingently Decouple Attention During Triadic Interactions

We hypothesized that contingent G-H and H-H decoupling would predict infant communicative development, because such decoupling suggests sensitivity to a partner's specific actions. For instance, infants tended to shift *gaze* from a held object to objects picked up by their mother (i.e., contingent G-H decoupling), but shifted a *hand* to objects dropped by the mother (contingent H-H decoupling). This suggests that infants redirect *gaze* to jointly attend-to or monitor a partner's actions, whereas they redirect *hands* to explore or use a new object. Thus infant decoupling is deployed selectively in triadic interactions. In fact, decoupling might be promoted by caregivers' sensitive triadic behaviors. For example, whenever the mother put down a toy it gave the infant an opportunity to manipulate a new object. This would especially engage infants older than 5-6 months, when reaching and grasping skills start to consolidate.

Additionally, from 4 to 9 months infants' bimanual activity changes its contingent relation to maternal action. At 4 months infants primarily decoupled hands when their mother picked up a toy, but at 9 months infant decoupled hands more after their mother dropped a toy. This implies a shift in infants' focus from caregiver-manipulated objects to objects that the caregiver makes accessible for manual exploration.

Other evidence suggests that decoupling might be related to triadic social actions. For example, H-H and G-H contingent decoupling was correlated with overall decoupling rates in rmcorr analyses. One possible interpretation is that contingent triadic interactions facilitate overall decoupling skills. In fact, most (~70%) H-H decoupling at 9 months was contingent: typically, infants decoupled hands to manipulate an object recently handled by their mother. This supports de Barbaro et al.'s (2013; 2016) claim that older infants slowly learn to participate in triadic play while maintaining attention to, or control over, toys they are holding (2016). This pattern also suggests that as infants increasingly decouple, their object choices are associated with caregivers' actions.

4.3. Infants Show Systematic Individual Differences In Decoupling Development

Results also partly support the hypothesis that infants can be classified by different developing decoupling trajectories, confirming and extending de Barbaro et al. (2016). Distinct higher- and lower-decoupling-trajectory subgroups were identified by longitudinal k-means clustering. For G-H decoupling, a high group showed more decoupling only at 4 months, whereas for H-H decoupling, a high group was distinct by 4 months, and continued to show increasing and higher decoupling at 6 and 9 months. One possible explanation for these different patterns is that because gaze-shifting skill develops earlier than manual skill, G-H decoupling is an indicator of attentional maturation only at younger ages (< 6 months), but is not diagnostic of individual differences in older neurotypical infants. Conversely, because infant manual shifting skills emerge later, H-H decoupling rates are normatively low at 4 months, and individual differences emerge later (i.e., second half of first year) as an indicator of attention-distributing skill, and possibly of triadic skills.

Although high G-H and high H-H decoupling groups did not overlap significantly more than chance, we found general correlations between G-H and H-H decoupling. Rmcorrs show significant longitudinal associations between changing G-H and H-H decoupling trajectories. This might indicate that although H-H and G-H decoupling develop in different trajectories, with H-H emerging later, infants who show more decoupling of gaze and hands also demonstrate more decoupling of their left and right hands, even at 9 months. We therefore cannot rule out the possibility that H-H and G-H decoupling share some common resources or processes. These resources facilitate distributing attention across sensorimotor modalities. That facilitation might in turn promote more dynamic (e.g., triadic) social interactions – a possibility that this study also addressed, as we shall now consider.

4.4. Decoupling Is Associated With Infants' Social And Communication Skills

The results suggest that infant sensorimotor decoupling is associated with social transactions during triadic play. Infant contingent decoupling was correlated with maternal toy handling rate. Also, the Low vs. High decoupling groups significantly differed in contingent hand shifts to initiate G-H decoupling at 4 months. This suggests that High-decouplers shift their hands more to engage with toys manipulated by caregivers.

Additionally, contingent decoupling predicted infants' later communication skills. Contingent G-H decoupling at 6 months predicted BSID-III communication scores at 18 months. One interpretation is that contingent attention-shifts facilitate triadic interactions, in which reciprocal actions reduce the inherent ambiguity of caregivers' referential speech, and thus indirectly promote language learning. Previous studies also suggest that decoupling might facilitate infants' action-organization skills. For example, from late infancy there is increasingly elaborate toy handling within social interactions (e.g, Parten, 1933; Semrud-Clikeman, 2007; Libertus & Hauf, 2017). Thus, developing the ability to distribute attention and actions might alter infants' social and pragmatic interactions in multiple ways.

4.5. Decoupling Is Associated With Infants' Motor Development

Results also partly support the hypothesis that decoupling is associated with infants' motor development. Previous studies have shown that the development of infant motor skills is associated with social interactions involving objects (Aureli, Presaghi, & Garito, 2018). Furthermore, motor development is associated with changes in visual attention (Pereira, Smith, & Yu, 2014). At 4 months, infants typically manipulate and look at a single object (de Barbaro et al., 2016). Between 4.5 and 7.5 months, infants increasingly sit unsupported, which improves controlled manual and visual attention to particular objects (Soska, Adolph & Johnson, 2010). Later, by 9 months, infants increasingly decouple their sensory modalities and motor actuators to divide attention between objects (de Barbaro et al., 2016). Our results are partly consistent with these findings. G-H decoupling at 6 months predicted composite motor scores at 12 months. A possible interpretation is that decoupling facilitates complex caregiver-infant interactions that reciprocally facilitate the development of more sophisticated motor skills. Furthermore, contingent H-H decoupling at 9 months predicted gross motor scores at 12 months, and overall G-H decoupling at 6 months predicted fine motor scores at 12 months. Gross motor skills allow infants to control their head and torso, and move their arms independently (Thelen & Spencer, 1998), for more advanced object play. Fine motor skills, by contrast, permit visually-guided reaching, and grasping and manipulating objects (Feldman, & Chaves-Gnecco, 2017). This might suggest that H-H vs. G-H decoupling facilitate somewhat different motor skills: whereas H-H decoupling might promote coordination of upper-body muscle groups (e.g., to retrieve objects from farther away), G-H decoupling might promote more precise coordination of ocular and manual muscle groups for planned actions. These findings fit the hypothesis that motor development facilitates decoupling by coordinating attention to objects within reach or offered by caregivers. However, infant BSID motor scores were not correlated with decoupling rates at other months, and motor milestones ages were not significantly associated with decoupling, so decoupling development is not simplistically related to overall motor development.

4.6. Summary, Limitations, and Implications

In conclusion, infants' sensorimotor decoupling of gaze and manual action develops from 4 to 9 months, and is partly contingent on caregivers' object manipulations. When caregivers drop or offer objects, it provides opportunities for infants to decouple attention, and by 6 months infants more effectively deploy an arm to respond. Furthermore, individual differences in G-H decoupling are significant at 4 months, but attenuated later - possibly because gaze-control develops earlier and consolidates soon after precision reaching and grasping skills emerge, typically around 4-5 months (von Hofsten, 1989). However, individual differences in H-H decoupling are detectable by 4 months, and persist through 9 months. Therefore, although triadic interactions are typically believed to emerge around 9 to 12 months, individual differences in sensorimotor abilities that could support these interactions are measurable by 4 months, and might predict later triadic engagement (Vaughan et al., 2003). Therefore, studies of triadic development should consider sensorimotor and attention-distributing skills in the first 6 months. Relatedly, individual differences in decoupling measures were associated with several motor and social skill indices. These findings suggest that decoupling is associated with other social skills, and with variability in caregivers' behaviors. However, High and Low decoupling group assignment did not predict motor or social outcomes, suggesting that a simple categorization of infants into High and Low decoupling groups might not sensitively capture relations between decoupling tendencies and later motor and social skills that contribute to triadic interactions.

This study has several limitations. Firstly, our participants represented a WEIRD population (Henrich et al., 2010) whose dyadic interactions differ in documented ways from infant-caregiver dyads in other cultures (e.g., Little et al., 2016). It will be important to replicate this investigation with infants and caregivers from diverse cultural and caregiving backgrounds before making any generalizations. Second, although the data were collected in naturalistic settings (i.e., participants' homes) interactions were constrained: infants were in fixed infant seats and dyad were alone, without other family members present. It is unclear how this feature corresponds to various naturalistic infant-care scenarios around the globe. Third, Hand-Hand decoupling might have been constrained by the affordances of the toys (e.g., Bourgeois et al., 2005). Future studies of infant triadic interactions should consider object properties, and systematically vary object affordances (and, e.g., visual salience). However, because there were several toys at each session, and because some object properties were controlled across months, we doubt that age differences in decoupling are simply due to idiosyncratic toy properties. Moreover, all dyads had the same toys at a given month, so this would not explain individual differences in infants' decoupling or in caregivers' behaviors. Fourth, mothers produced other variable actions (e.g., pointing; emotional expressions) to modulate infants' response. Those variable actions were not considered in these analyses, partly because the high dimensionality of a model that would include all such variables would require a very large dataset. We should therefore consider the current results as preliminary, and in need of replication. We also emphasize that other factors (e.g., caregiver behaviors) likely modulate or interact with infant decoupling in as-yet unknown ways. For example, maternal speech was not taken into account, although previous work showed that object-naming increases during infant object explorations (Chang, de Barbaro & Deák, 2016). Infant-directed speech might have further influenced infants' attention during decoupling events – this could be tested in future studies.

These results raise questions about children at risk of developmental delays. Some at-risk infants show delayed motor development. For example, children with autism have delayed gross and fine motor skills (Liu & Breslin, 2013; Gernsbacher et al., 2008), and children at risk for autism and other syndromes tend to show delayed social skills such as gaze-following (Leekam, Hunnisett, & Moore,1998; Leekam et al., 2000), initiation of joint attention (Garretson et al., 1990; Bruinsma et al., 2004), and gaze alternation during triadic interactions (Mundy et al., 1986). Because decoupling skills show some associations with both motor and communicative skills, atypical emergence of sensorimotor decoupling might prove informative as a secondary predictor of atypical development.

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Ethics statement

The research methods for this study were approved by the authors' Institutional Review Board, and met Federal guidelines for the ethical treatment of human research participants.

Data Availability Statement

The data and analysis codes are available at: https://osf.io/bnyhk/.