Individual Differences in the Maternal Context of Infant Sensorimotor Decoupling: A Longitudinal Study From 4 to 9 Months of Age

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Introduction

Mother-infant triadic interactions, wherein the infant coordinates attention between a social partner and an object of shared focus (Striano & Reid, 2006), facilitates infants' learning of social and praxis skills, such as intentional actions on objects (Brandone, Stout, & Moty, 2019), word meanings (Carpenter, Nagell, & Tomasello, 1998), eye-gaze cues (Striano & Reid, 2006), and social routines (Rochat et al. 2016). At month 3, infants are sensitive to adults' gaze shifts in triadic interactions (Striano & Reid, 2006), and are starting to coordinate their attention between a caregiver and objects during shared book-reading activities (Rossmanith et al. 2014). It is commonly asserted that triadic engagement emerges around 9 to 12 months of age (Carpenter et al., 1998). Before 9 months infants primarily engage in dyadic interactions either with a social partner or an object, but seldom coordinate their attention between both. However, by 12 months most infants can smoothly switch attention between a caregiver and shared objects (de Barbaro et al., 2016). According to de Barbaro et al. (2015), one challenge of triadic attention is attending to the toy the caregiver is playing with, while maintaining attention towards objects that the infants were already playing with. From month 4 to month 12, infants gradually acquire this ability as they develop the decoupling or their sensorimotor modalities (e.g., gaze; manual skills).

According to de Barbaro et al. (2015), infant's development of sensorimotor decoupling from 4 to 12 months allows them to shift from dyadic to triadic interactions. Sensorimotor decoupling occurs when the infant is directing their gaze and hands to different objects. At month 4, infants converge both their haptic and visual modalities onto a single object introduced by a caregiver; from 6 to 12 months infants increasingly decouple modalities across objects manipulated by the adult and by themselves (de Barbaro et al., 2012). This allows infants to jointly manipulate a toy with their parents while manipulating other toys by themselves. Particularly, according to de Barbaro et al. (2012), around 6 months infants seem to be in a transitional period. They divided infants into a Mature and an Immature group by a median split of Gaze-Hand decoupling rates at 6 months. Infants in the Mature group showed decoupling rates comparable to 9-month-olds, and those in the Immature group showed rates indistinguishable from 4-month-olds.

This study is a follow-up of de Barbaro et al. 's (2012) findings that 6-month-olds could be categorized as a Mature and an Immature Decoupling group. Firstly, in their study, it was unclear what maternal activities might elicit infant decoupling. Here we investigate infant decoupling contingent with mother manual actions. Secondly, in their study, the Mature and Immature groups were categorized based only on the infants' decoupling rate at month 6. Here we classify infants' decoupling development based on longitudinal changes in decoupling rates across months 4, 6 and 9. Thirdly, in the original study, the contributing factors of this difference in decoupling rate was unclear. We explore whether the differences in decoupling development are correlated with sensorimotor development and the mother's object-handling rates.

Firstly we hypothesize that the rate of Hand-Hand and Gaze-Hand decoupling in contingent with mother manual actions increases with age. Secondly we hypothesize that unsupervised clustering of longitudinal decoupling data would also result in a High Decoupling group and a Low Decoupling group, similar to Barbaro et al. (2012). Thirdly we hypothesize that longitudinal development of decoupling might be correlated with the development of the infant's social skills and maternal manual activities during toy-play.

Methods

Participants

The participants were 42 mother-infant dyads enrolled in a longitudinal study of infant social development. This sample of convenience was recruited from the greater San Diego area. Four participants were excluded from analysis due to equipment failure or use of non-English language, resulting in a sample of 38 dyads. The mothers' mean age upon recruitment was 32.1 years (range = 21-42), with an average of 16.1 years of formal education (range = 12-21). Parents reported that 29 infants were Caucasian, four were Hispanic, two were Asian, five were "other" or multiracial, and two parents provided no information about race or ethnicity. No infants had any neurological, cognitive, or sensory deficits, according to parents (Chang & Deak, 2019).

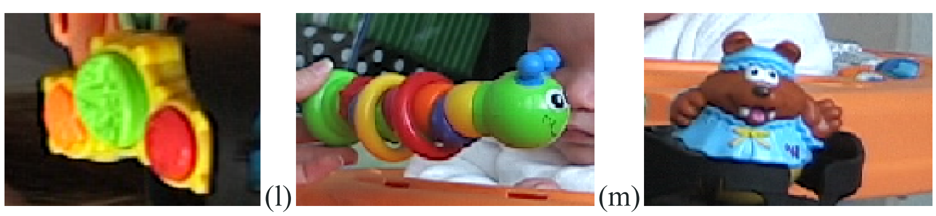
Materials

Testing environment. Dyads were recorded in their homes. The participants were seated on the floor. The infants at 4, 6, and 9 months sat in a play seat with a tray, face-to-face with their mothers. Three Canon mini-DV video cameras recorded, respectively, (1) the infant's upper body and head, and the tray; (2) the mother's upper body and head; and (3) the dyad in profile view (see Figure 1).

Toys. At months 4, 6, and 9, three toys were placed on the tray or in cups mounted on each side of the tray. The toy set at each month included one toy that makes sounds ("musical");

one with a face ("animate"); and one typical infant toy with neither sound-making parts nor a face ("inanimate"). At month 4 the toys were a plastic caterpillar, a plastic toy with sound-producing buttons, and a plastic rounded-bottom wobbling animal (see Figure 2a). At month 6 the toys were a foam soccer ball, a different wobbling animal, and a plastic triangle with sound-producing buttons (see Figure 2b) At month 9 the toys were a soccer ball, a third wobbling animal, and a sound-producing rattle. (see Figure 2c; de Barbaro et al., 2015)

Figure 1



(l) (m) (r)

Figure 2(a): 4 month toys, l-r: inanimate, musical, and animate toy

(l) (m) (r)

Figure 2(b): 6 month toys (l-r): inanimate, musical, and animate toy

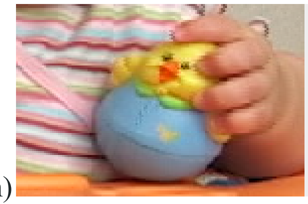
 (l)  (m)  (r)

Figure 2(c): 9 month toys (l-r): inanimate, musical, and animate

Procedure

Videos of mother-infant free play sessions were recorded at their homes. The first 5-6 min was an unscripted toy play period; the subsequent 5-6 min was an unscripted attention-directing period. Because infants had access to the toys only during the toy play period, only the toy play sessions are analyzed for this study. The average toy play session duration was 267.3 seconds at month 4 (range = 167s - 450s), 321.1 sec at month 6 (range = 242s - 505s), and 333.8 sec at month 9 (range = 186s - 589s).

Infants' and mothers' object-handling activities, as well as infants' gaze fixations, were coded by randomly assigned, trained coders at 10Hz precision using ELAN (http://www.lat-mpi.eu/tools/elan/). Files were checked for consistency by an experienced staff researcher or graduate student. To check reliability, sessions samples were quasi-randomly selected from each month and independently transcribed by a second coder. 33% of the entire sample was re-coded for infant hands, 37% was re-coded for mother hands, and 33% was re-coded for infant gaze. Cohen's kappas (Cohen, 1968) averaged 0.85 for infant hands, 0.92 for mother hands, and 0.79 for infant gaze (see also Chang & Deak, 2019)

Infant gaze fixation coding. Trained coders coded the onset and offset time of infant gaze fixations, and whether the infant was looking at the toys, the mother, or other places.

Object-handling activity coding. Trained coders coded the onset and offset time of handling events, and the number and identities of toys the participant was holding. Manual activity was coded for mothers and infants respectively. These codes were synthesized into dyadic handling states, as defined in **table 1** below.

Dyadic hand state	**Definition**	**Example**
mother 0, infant 0	Mother (Mo) holding 0 toys; infant (Inf) holding 0 toys	Neither Mo nor Inf holding any object
mother 0, infant 1	Mo holding 0 toys; Inf holding 1 toy	Mo holding nothing; Inf holding animate toy
mother 0, infant 2	The mother is holding 0 toys, and the infant is holding 2 toys	Mo holding nothing; Inf holding animate toy and inanimate toy
mother 1, infant 0	The mother is holding 1 toy, and the infant is holding 0 toys	Mo holding animate toy; Inf holding nothing
mother 1, infant 1	The mother is holding 1 toy, and the infant is holding 1 toy	Mo holding animate toy; Inf holding inanimate toy
mother 1, infant 2	The mother is holding 1 toy, and the infant is holding 2 toys	Mo holding animate toy; Inf holding inanimate toy and musical toy

mother 2, infant 0	The mother is holding 2 toys, and the infant is holding 0 toy	Mo holding animate toy and inanimate toy; Inf holding nothing
mother 2, infant 1	The mother is holding 2 toys, and the infant is holding 1 toy	Mo holding animate toy and inanimate toy; Inf holding musical toy
mother 2, infant 2	The mother is holding 2 toys, and the infant is holding 2 toys	Mo holding animate toy and inanimate toy; Inf holding musical toy and animate toy

Table 1

Statistical analysis

Data were analyzed using Python 3 and RStudio (v4.0.3).

Mother manual activities. Each of a mother's discrete manual activities was categorized as a pick-up, touch, or drop. A pick-up occurs when the mother touches a toy that was not touched in the previous manual action. A touch occurs when the mother continues to touch a toy in two consecutive manual actions. A drop occurs when the mother stops touching a toy that was touched in the previous manual action.

Infant Hand-Hand decoupling rate. Hand-Hand (H-H) decoupling occurs when the infant's two hands are in contact with two different toys. Hand-Hand decoupling rate is calculated as the number of frames in which the infant's two hands were touching two different objects, divided by the total number of frames in which the infant was touching any toy.

Infant Gaze-Hand decoupling rate. Gaze-Hand (G-H) decoupling occurs when the infant's gaze and hands are directed to different objects. Gaze-Hand decoupling rate is calculated as the number of frames in which the infant was looking at and touching two different toys, divided by the total number of frames in which the infant is touching any toy. (Note that because infants are virtually always looking at something, it is sensible to use the total number of touching frames as the denominator.)

Infant Contingent decoupling rate. Contingent decoupling occurs when the infant touches the toy the mother is handling within 5 sec after the mother picks it up or drops it. Contingent decoupling rate is calculated as the number of frames of decoupling events that occurred within 5 sec after a mother picks up, touches, or drops a toy that the infant either looks at or touches in the decoupling event, divided by the total number of frames of decoupling events.

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

Results

Comparisons across different months were analyzed using repeated-measures one-way analysis of variance(rmANOVA). Post hoc tests were used for pairwise multiple comparisons to assess the differences of each subject between different months. Infants with less than two manual activities per session were excluded from the analyses, resulting in 33 dyads being analyzed longitudinal across months 4, 6 and 9.

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

Infant manual activity rate. Manual activity rate is calculated as the number of infant picking and dropping activities per minute. A rmANOVA test shows a significant difference in infant manual activity rate across months 4, 6 and 9 ($F(2, 84) = 13.51$, $p < 0.0001$). Post hoc tests show significant increases from month 4 ($X = 1.97$, $SD = 1.61$) to 6 ($X = 3.83$, $SD = 2.62$), $p = .0004$; and from month 4 to 9 ($X = 4.71$, $SD = 3.26$), $p = .000015$. The difference between 6 and 9 months, however, was not significant ($p = 0.18$).

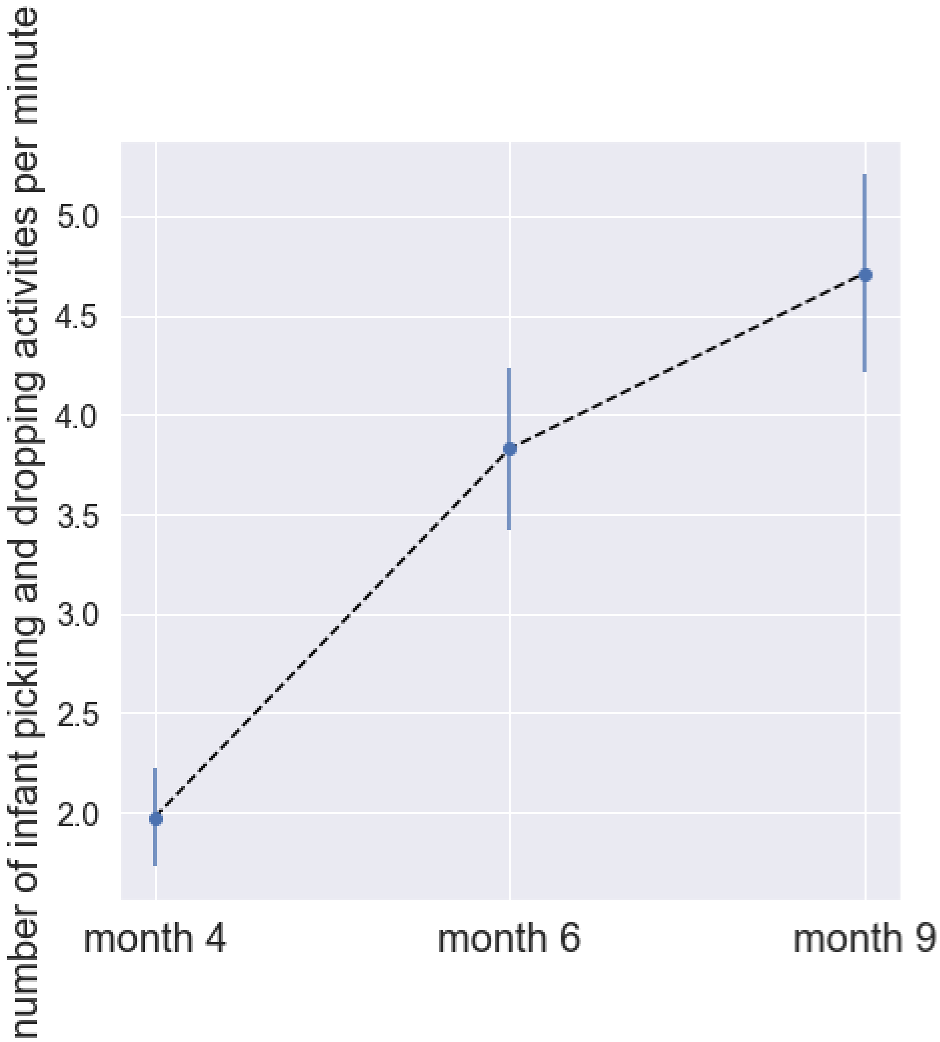


Figure 3. Y-axis: mean number of infant hand actions.Error bar = SE_{mean}, * $p < 0.05$.

Infant visual fixation rate. Infant visual fixation rate is calculated as the number of times the infant looks at the three toys and the mother per session, respectively. A rmANOVA test shows a significant difference in infant visual fixation rate across months 4, 6 and 9 ($F(2, 84) = 6.10$, $p = 0.0034$). Post hoc tests show a marginal increase in infants' visual fixation rate from month 4 (X = 35.47, SD = 6.29) to 6 (X = 44.74, SD = 5.23), $p = 0.051$; and a significant increase from month 4 to 9 (X = 46.74, SD = 5.32); $p = 0.013$; however, the difference from month 6 to 9 is not significant ($p = 0.61$).

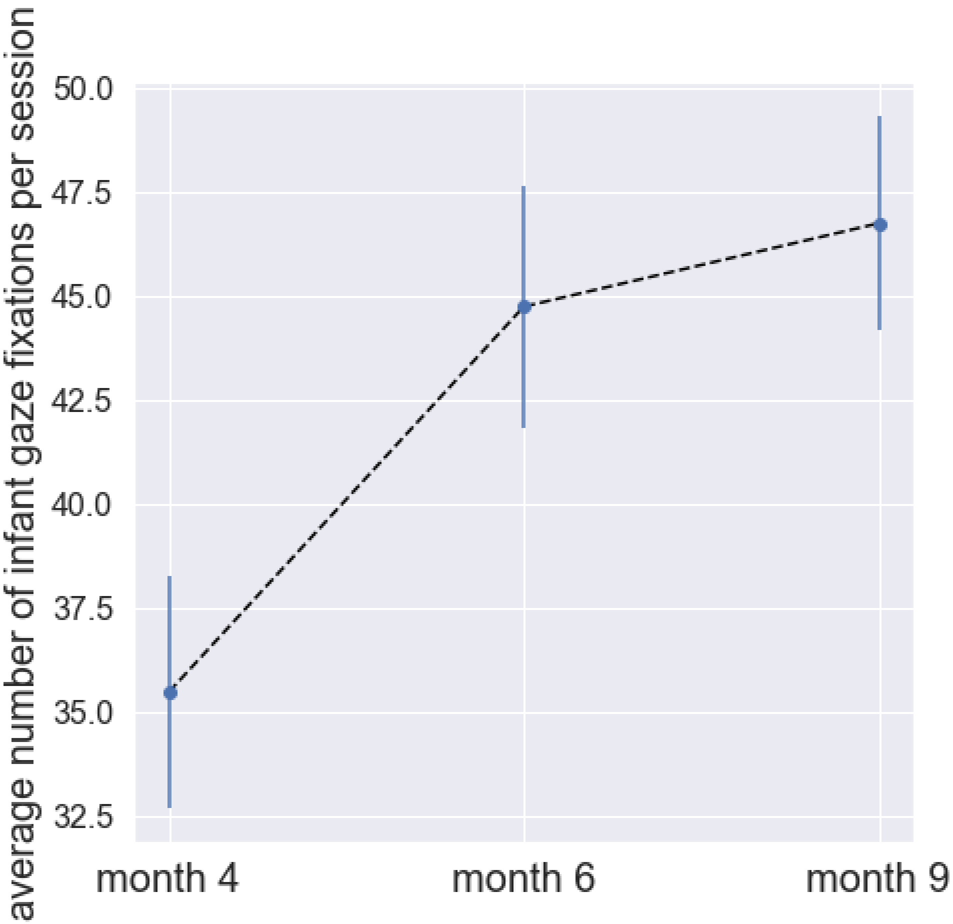


Figure 4. Y-axis: average number of infant gaze fixations, error bar = SE_{mean}.

Infant-initiated object handling rate. Infant-initiated object handling rate is calculated as the number of instances per minute a toy that had been unattended for over 5 seconds was picked up by the infant. A rmANOVA test shows a significant difference in infant-initiated object handling rate across months 4, 6 and 9 ($F(2, 84) = 12.21$, $p = 0.00022$). Post hoc tests show a significant increase in the rate of these events from month 4 (X = 1.52, SD = 1.34) to 6 (X = 3.21, SD = 2.46), $p = 0.0037$; and from month 4 to 9 (X = 3.58, SD = 2.56), $p < 0.0001$; but not from month 6 to 9 ($p = 0.51$).

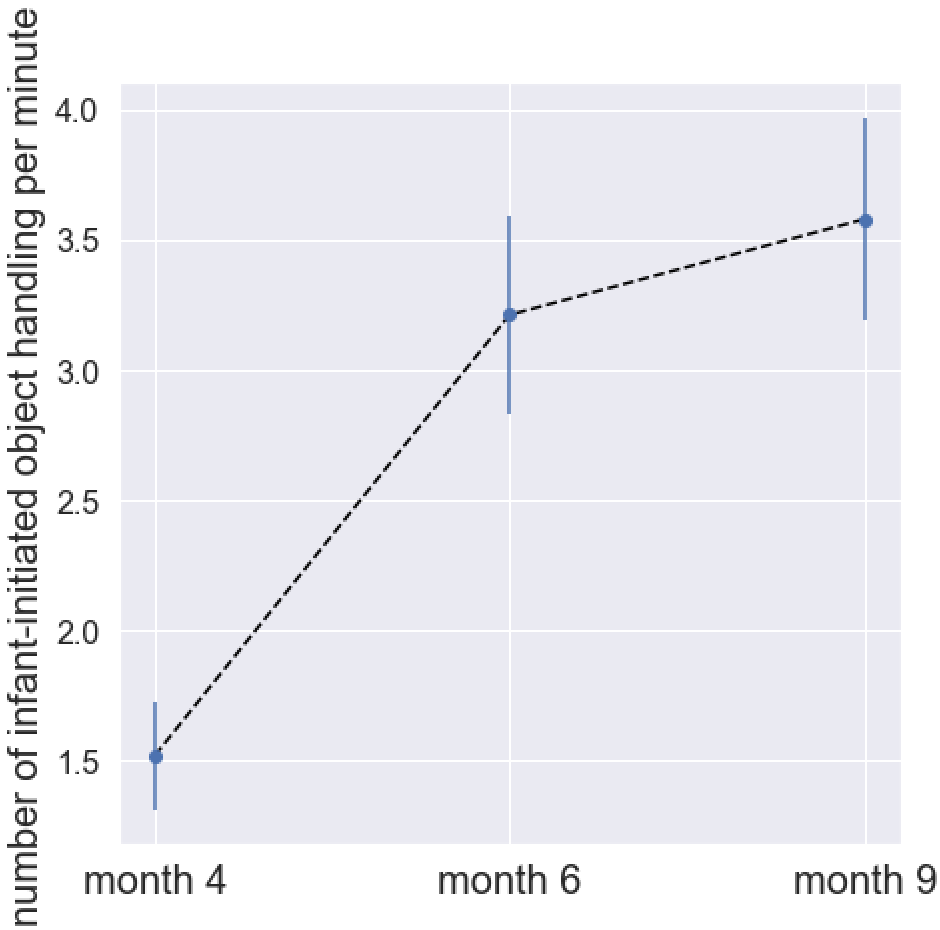


Figure 5. Y-axis: average rate of infant-initiated object handling actions per minute, error bar = SE_{mean}.

Infant multiple-toy handling rate. Infant multiple-toy handling rate is calculated as the number of instances of infants simultaneously touching two toys per minute. A rmANOVA test shows a significant difference in infant multiple-toy handling rate across months 4, 6 and 9 ($F(2, 84) = 12.82$, $p < 0.0001$). Post hoc test shows an increase in rate of infant handling of multiple toys per minute from month 4 (X = 0.26, SD = 0.46) to 6 (X = 0.57, SD = 0.74), $p = 0.02$; and from month 6 to 9 (X = 1.18, SD = 1.26), $p = 0.018$. The difference between month 4 and 9 is also significant ($p = 0.0008$).

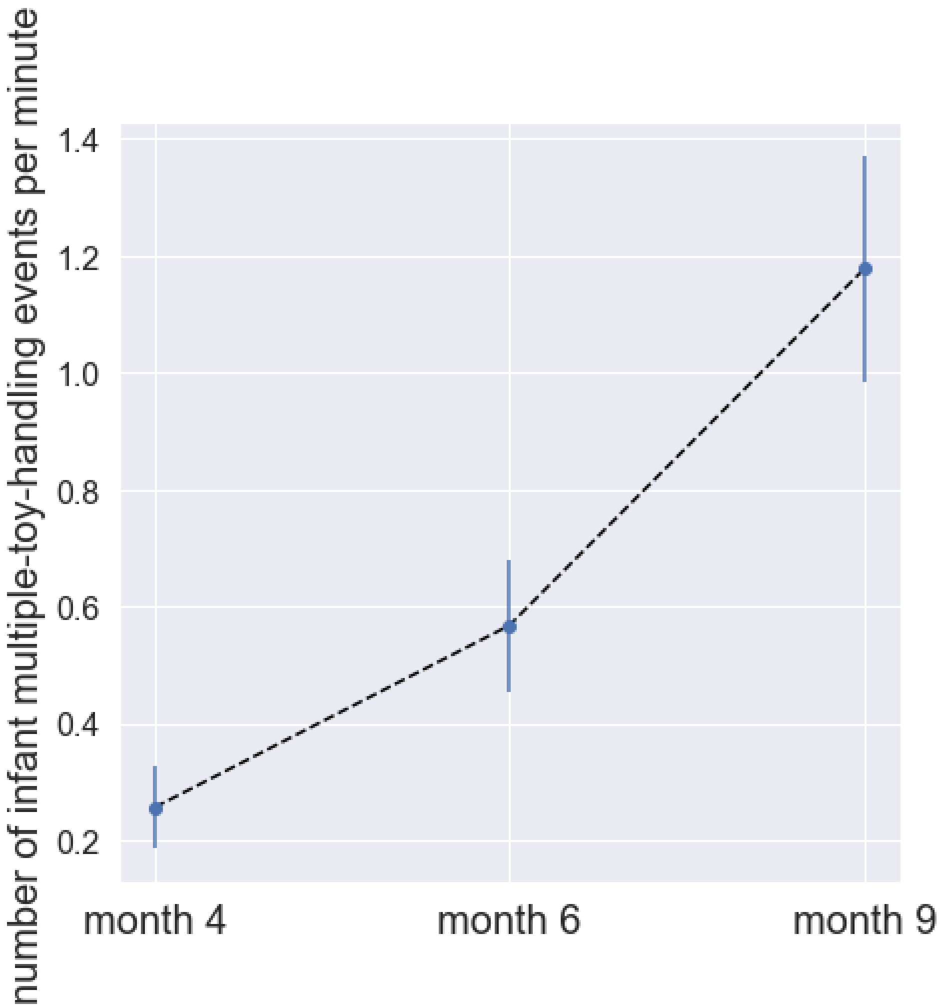


Figure 6. Y-axis: rate of infant handling multiple toys per minute, error bar = SE_{mean}.

2. Rate of Hand-Hand and Gaze-Hand decoupling increases with age.

Hand-Hand decoupling. A rmANOVA test shows a significant difference in Hand-Hand decoupling proportions across months 4, 6 and 9 ($F(2, 78) = 14.00$, $p < 0.0001$). Post hoc tests shows a significant increase from month 4 (X = 0.062, SD = 0.13) to 9 (X = 0.22, SD = 0.22), $p = 0.0008$; and from month 6 (X = 0.084, SD = 0.11) to 9, $p = 0.002$; but not from month 4 to 6 ($p = 0.44$).

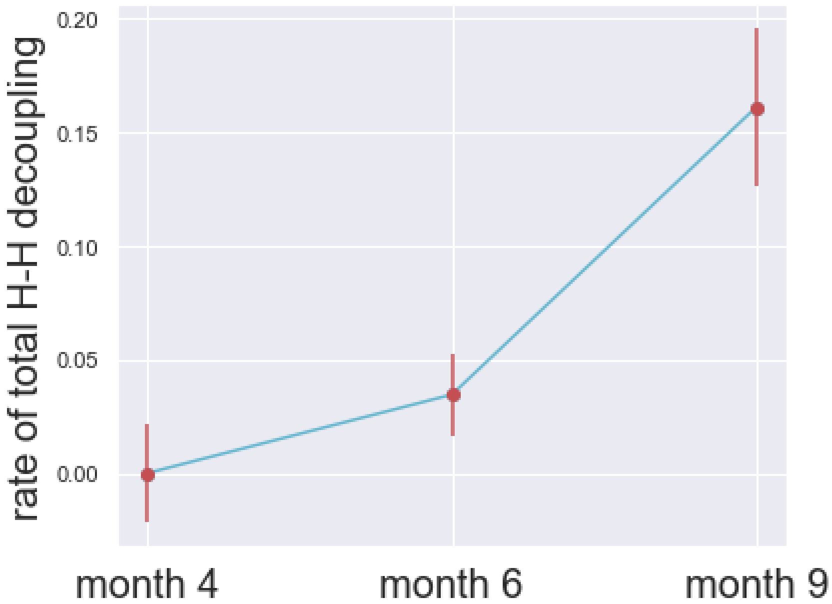


Figure 7. Mean of Hand-Hand decoupling rate across months 4, 6 and 9, error bar = SE_{mean}.

Gaze-Hand decoupling. A rmANOVA test shows a significant difference in the proportion of Gaze-Hand decoupling across months 4, 6 and 9 ($F(2, 80) = 12.66$, $p < 0.0001$). Post hoc test shows a significant increase from month 4 ($X = 0.45$, $SD = 0.30$) to 9 ($X = 0.70$, $SD = 0.19$), $p < 0.0001$; and from month 6 ($X = 0.50$, $SD = 0.22$) to 9, $p =0.00012$; but not from month 4 to 6 ($p = 0.38$).

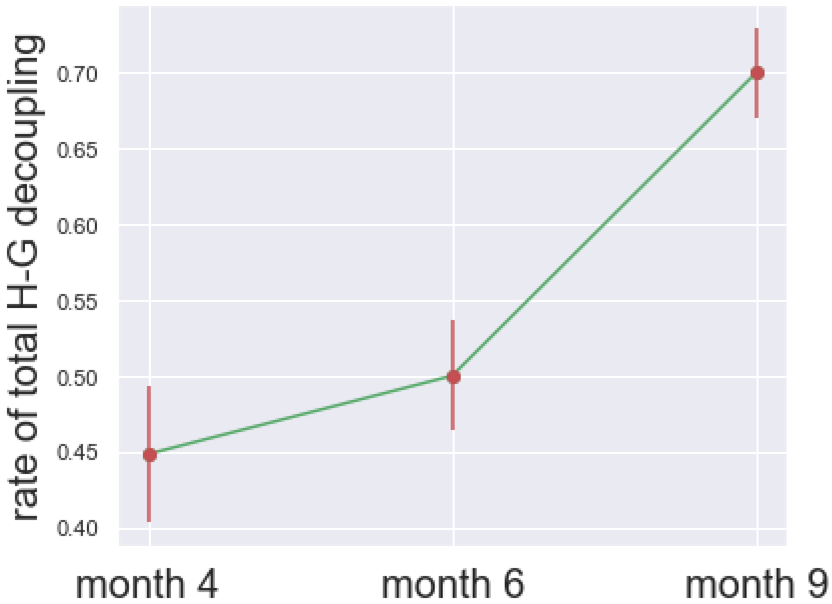


Figure 8. Mean of Hand-Gaze decoupling rate across months 4, 6 and 9, error bar = SE_{mean}.

3. Rate of Hand-Hand and Gaze-Hand decoupling contingent with mother manual actions increases with age.

Contingent Hand-Hand decoupling. A rmANOVA test shows a significant difference in the proportion of Hand-Hand decoupling contingent on mothers' manual actions between months 4, 6 and 9 ($F(2, 78) = 9.41$, $p = 0.00022$). Post hoc test shows a significant increase from month 4 ($X = 0.39$, $SD = 0.47$) to 9 ($X = 0.74$, $SD = 0.43$), $p = 0.0007$; and from month 6 ($X = 0.50$, $SD = 0.32$) to 9, $p = 0.010$; but not from month 4 to 6 ($p = 0.34$).

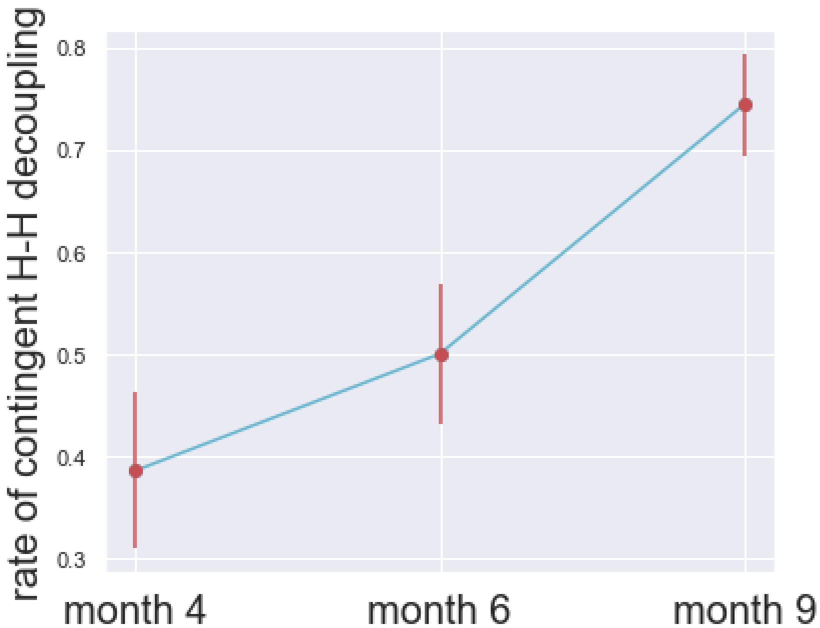


Figure 9. Mean of contingent Hand-Hand decoupling rate across months 4, 6 and 9, error bar = SE_{mean}.

Contingent Gaze-Hand decoupling. A rmANOVA test shows a significant difference in the proportion of Gaze-Hand decoupling contingent on mother manual activities across months 4, 6 and 9 ($F(2, 78) = 11.17$, $p < 0.0001$). Post hoc test shows a significant increase from month 4 ($X = 0.15$, $SD = 0.19$) to 9 ($X = 0.30$, $SD = 0.18$), $p = 0.0014$; and from month 6 ($X = 0.19$, $SD = 0.16$) to 9, $p = 0.012$; but not from month 4 to 6 ($p = 0.27$).

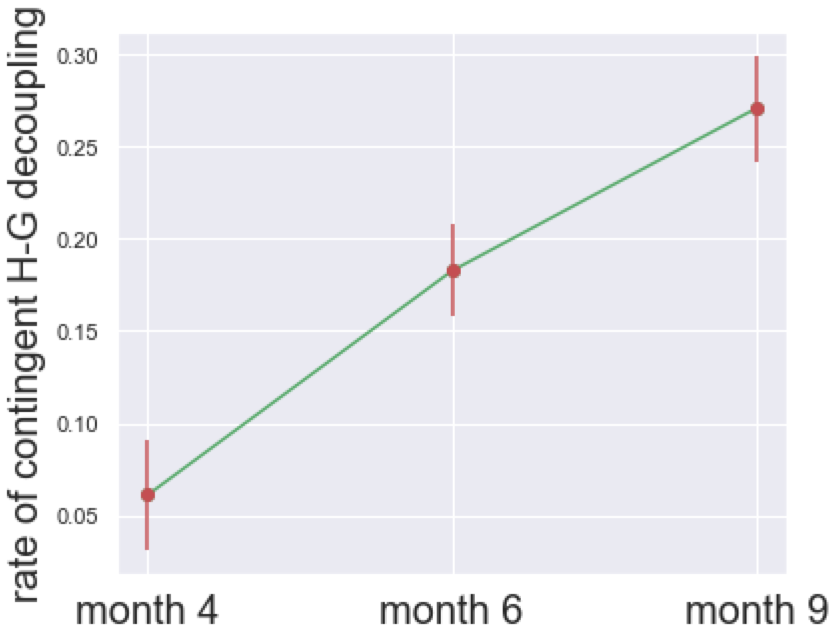


Figure 10. Mean of contingent Gaze-Hand decoupling rate across months 4, 6 and 9, errorbar = SEmean.

4. K-means longitudinal classification of High Decoupling and Low Decoupling groups.

Based on the longitudinal pattern of Hand-Hand decoupling rates, KmlShape classified infants into a Low Decoupling group and a High Decoupling group. Then we looked at the differences in the longitudinal Hand-Gaze decoupling rates between these two groups. The difference between the two groups emerges at month 6. The Low group has a low rate of H-H decoupling at month 6 (X = 0.0033; SD = 0.062). The High Decoupling group has a higher rate of H-H decoupling at month 6 (X = 0.094; SD =0.13). A one-way ANOVA test shows a significant difference in H-H decoupling between groups at month 6 ($p = 0.015$), and at month 9 (Low: X = 0.049; SD = 0.056; High: X = 0.26; SD = 0.22; $p = 0.00015$).

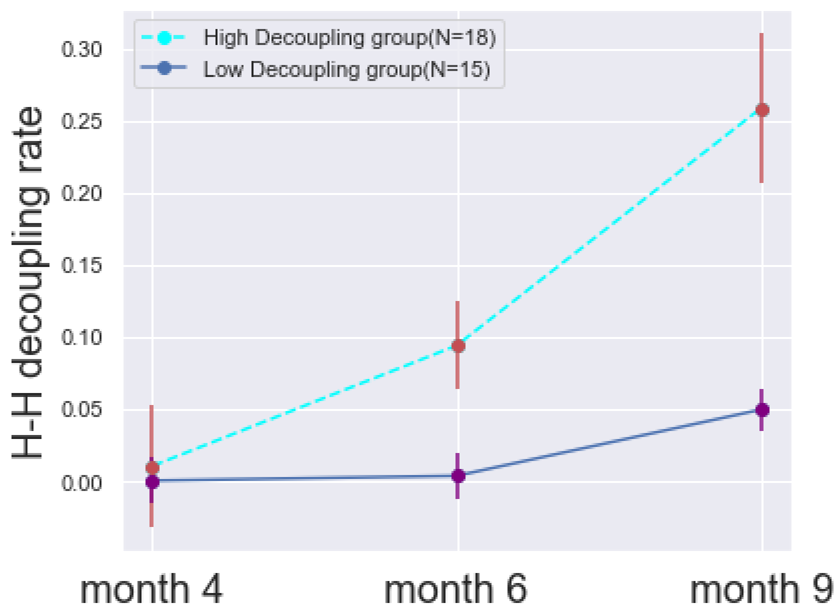


Figure 11. Low Decoupling group (solid blue line) and High Decoupling group (dashed cyan line) median Hand-Hand decoupling rate, Low Decoupling group (red bar) and High Decoupling group (purple bar) error bar = SE_{mean}, *p<0.05 at month 6, ***p<0.001 at month 9.

The group difference in Hand-Gaze decoupling was not significant at month 6 (One-way ANOVA: (p = 0.89): Low group (X = 0.60; SD = 0.21);High (X = 0.82; SD = 0.12)). However, a difference emerges by month 9. A One-way ANOVA test shows a significant difference between the Low and High group (p = 0.0022). Moreover, Pearson correlation shows a significant positive correlation between H-H and H-G decoupling rate at month 9 (r = 0.56; p = 0.00080).

There is no significant difference in the rate of contingent H-H decoupling and contingent H-G decoupling across months 4, 6, and 9.

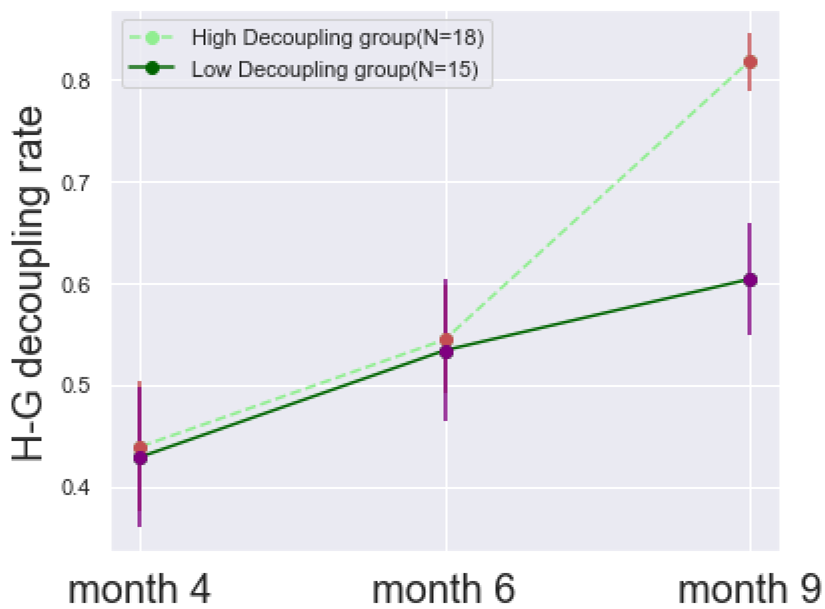


Figure 12. Low Decoupling group (solid dark green line) and High Decoupling group (dashed cyan line) median of Hand-Gaze decoupling rate, Low Decoupling group (red bar) and High Decoupling group (purple bar) error bar = SE_{mean}, $**p<0.01$ at month 9.

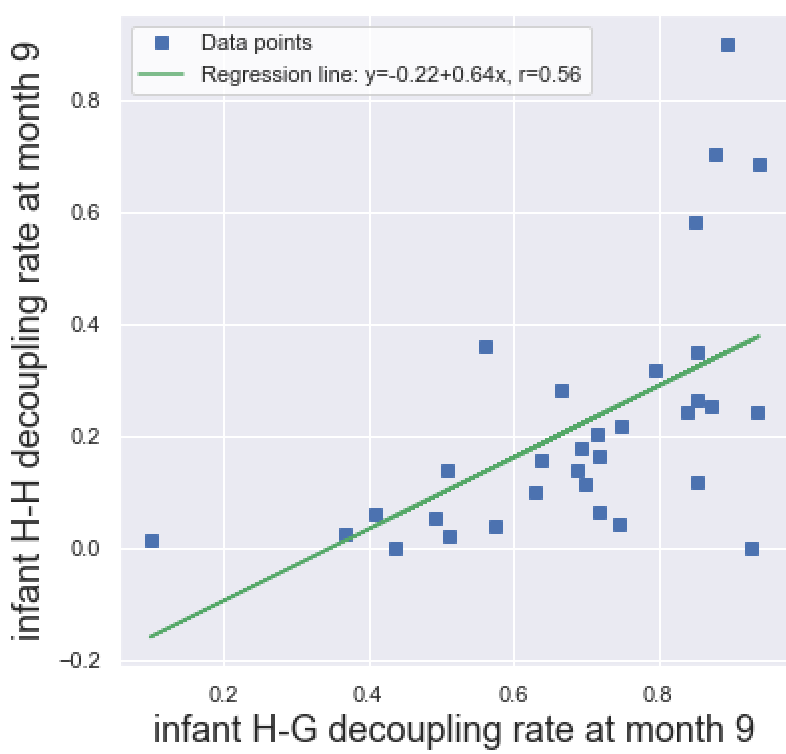


Figure 13. Correlation between infant Hand-Gaze decoupling rate and Hand-Hand decoupling rate at month 9. X axes is the infant Hand-Gaze decoupling rate at month 9, Y axes is the infant Hand-Hand decoupling rate at month 9.

5. Decoupling developmental differences is correlated with both the development of social skills and maternal manual activities.

The infant gaze- and pointing- following indicator was obtained from the study on infants' processing of adult social cues (Deák, 2015). Gaze and pointing milestone indicators reflect the development of the infants' ability of gaze- and pointing- following. A high score indicates that the infant is better at gaze- and point-following (Deák, 2015). A One-Way ANOVA test shows a significant difference in the gaze-/point-following indicator between the Low (X = 0.25; SD = 0.17) and High Decoupling group (X = 0.3625; SD = 0.11; $p = 0.0079$), see Figure 14.

Pearson's correlation shows a significant negative correlation between infant H-G decoupling rate and rate of mother manual actions at month 6 ($r = -0.69$; $p < 0.0001$).

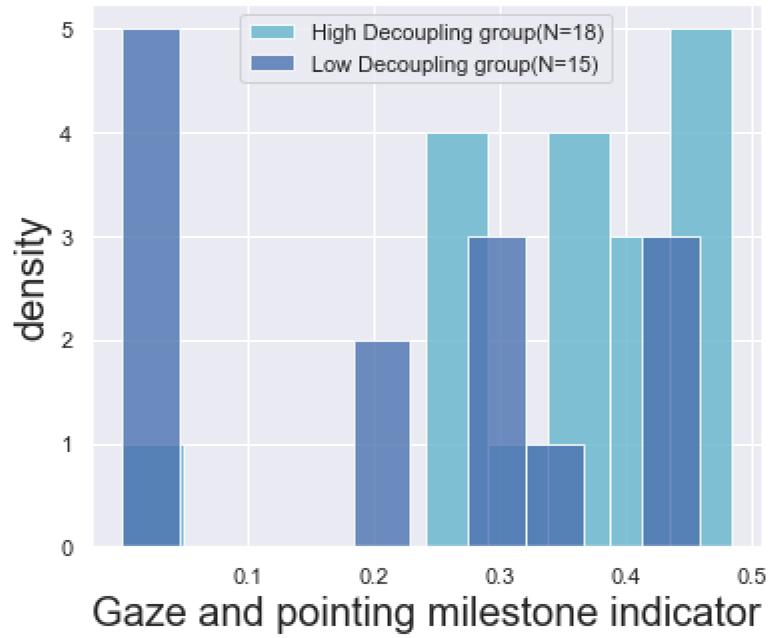


Figure 14. Histogram for the infant gaze-/point-following indicator for the High (cyan) and Low (blue) Decoupling groups; ***p*<0.01.

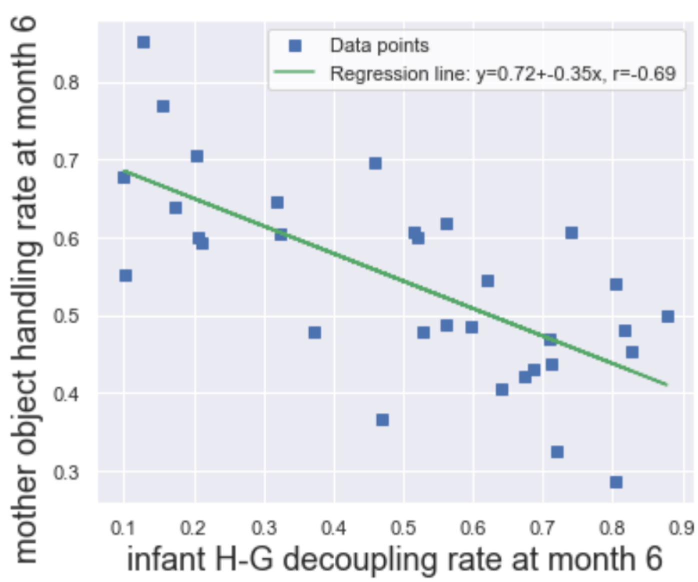


Figure 15. Correlation between infant Hand-Gaze decoupling rate and mother object handling rate at month 6. X axis: H-G decoupling rate at month 6; Y axis: mother;s object handling rate at month 6.

Discussion

From 4 to 9 months infants shift their visual and haptic modalities more frequently. Infants shift their gaze between objects and people more often, pick up and put down objects more often, and simultaneously touch and/or look at multiple objects more often. This indicates that they are developing sensorimotor skills that allow them to distribute their attention across multiple objects and people. Furthermore, infants from 4 to 9 months increasingly shift attention to objects unattended for over five seconds by their mother. This might indicate that the infant's focus of attention becomes less dominated by the mother's current object of attention. Therefore, infants might decreasingly converge both their hands and gaze towards the toy handled by the mother.

From 4 to 9 months infants also decouple their gaze and hands more frequently. Both Hand-Hand and Hand-Gaze decoupling increase as infants grow up. Particularly, the mean G-H decoupling at month 9 reached 0.7, which means that when infants touched a toy, around 70% of the time they were looking at objects other than the toy they were holding. This indicates the infants' robust emerging ability to distribute sensorimotor modalities across objects by 9 months.

Results support the hypothesis that infant's decoupling activities are more closely associated with mother's manual activities from 4 to 9 months. Both H-H and G-H decoupling contingent with mother manual activities increased across months. Particularly, the mean of contingent H-H decoupling at month 9 is around 0.75: when infants are touching two different toys, around 75% of the time they have deployed at least one hand to engage an object recently handled by the mother. This indicates that as infants are improving at decoupling modalities, their object choices are associated with social actions of caregivers. Infants increasingly participate in joint toy-play activities with their mothers while maintaining attention towards the toys they are handling.

Results also support the hypothesis that infants can be divided into a High and Low Decoupling group, based on their longitudinal trends in decoupling rates. K-means longitudinal clustering identified two groups of infants with different trajectories in tendencies to decouple. A High Decoupling group had developed more decoupling propensities by month 6, and continued to develop more decoupling activities at month 9. Although the two groups did not statistically differ in G-H decoupling at month 6, this index was positively correlated with H-H decoupling at month 9. This might indicate that although H-H decoupling and G-H decoupling develops in separate trajectories, infants that decouple their two hands more often are also likely to decouple gaze and hands more often by month 9. Therefore, H-H and G-H decoupling might share common sensorimotor resources that facilitate infants' abilities to distribute their attention across different objects. However, there is a natural dependency between H-H decoupling rate and H-G decoupling rate. When the infant is simultaneously holding two objects, they can only focus their gaze on one object at a time, leaving the other one visually unattended. Therefore, there is always a H-G decoupling event whenever there is a H-H decoupling event.

Results support the third hypothesis that the infant's development of decoupling abilities is associated with both infant social skill development and mothers' manual activities. Infants in the High Decoupling group are better at gaze- and pointing- following compared with infants in the Low Decoupling group. Gaze following allows infants to converge on a caregiver's focus of attention (Triesch et al., 2006) Therefore, infants with better gaze-following abilities might be more sensitive when the mother shifts to play with another toy, and they might decouple their hands more in response to the mother's shift of attention. Additionally, the infants' H-H decoupling rate is negatively correlated with the mothers' object handling frequency at month 6. A possible interpretation is that at month 6, infants who frequently decouple modalities are likely to have mothers that manipulate toys less frequently. Perhaps when mothers frequently pick up and drop toys, infants are more distracted by the mother's actions, and less likely to direct attention towards each toy handled by the mother, while also maintaining contact with the object they themselves were originally handling.

In conclusion, as infants develop decoupling abilities from 4 to 9 months, they increasingly decouple their most important exploratory modalities - gaze and manual touch - and this decoupling is partly contingent on their caregiver's ongoing object manipulations. In particular, when caregivers put down (offer) objects, this provides an opportunity for infants by around 6 months to decouple attention. The results further indicate that infants increasingly can engage in joint toy-play with their mother while maintaining attention towards other toys. This growing ability allows them to increasingly engage in triadic interactions. Furthermore, the individual differences in infant decoupling abilities emerge at month 6, and continue to grow at month 9. Therefore, although triadic interactions emerge around 9 to 12 months of age, individual differences in the abilities to engage in triadic attention can be traced back to 6 months of age, and individual differences at this age predict triadic skills in the months to come (Vaughan, Amy, et al. 2003). Therefore, studies of triadic interactions should consider developing sensorimotor and attention-allocating abilities in preceding months. Related to these possibilities, individual differences in infants' decoupling abilities were associated with better gaze- and point-following skills, and with an "optimal rate" with mothers manipulated toys. These findings suggest that infant decoupling might be associated with other infant social skills, as well as other variable behaviors by caregivers in their social environment.

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