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Mother-infant self- and interactive contingency at four months and infant cognition at one year: A view from microanalysis

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ABSTRACT

Although a considerable literature documents associations between early mother-infant interaction and cognitive outcomes in the first years of life, few studies examine the contributions of contingently coordinated mother-infant interaction to infant cognitive development. This study examined associations between the temporal dynamics of the contingent coordination of mother-infant face-to-face interaction at 4 months and cognitive performance on the Bayley Scales of Infant Development at age one year in a sample of (N = 100) Latina mother-infant pairs. Split-screen videotaped interactions were coded on a one second time base for the communication modalities of infant and mother gaze and facial affect, infant vocal affect, and mother touch. Multi-level time-series models evaluated self- and interactive contingent processes in these modalities and revealed 4-month patterns of interaction associated with higher one-year cognitive performance, not identified in prior studies. Infant and mother *self-contingency*, the moment-to-moment probability that the individual's prior behavior predicts the individual's future behavior, was the most robust measure associated with infant cognitive performance. Self-contingency findings showed that more varying infant behavior was optimal for higher infant cognitive performance, namely, greater modulation of negative affect; more stable maternal behavior was optimal for higher infant cognitive performance, namely, greater likelihood of sustaining positive facial affect. Although *interactive contingency* findings were sparse, they showed that, when mothers looked away, or dampened their faces to interest or mild negative facial affect, infants with higher 12-month cognitive performance were less likely to show negative vocal affect. We suggest that infant ability to modulate negative affect, and maternal ability to sustain positive affect, may be mutually reinforcing, together creating a dyadic climate that is associated with more optimal infant cognitive development.

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Early social interaction between infant and caregiver sets a powerful trajectory in development (Feldman, 2007; Jaffe et al., 2001; Sameroff, 2010; Thompson, 2008). This study examined the temporal dynamics of the contingent coordination of mother-infant face-to-face interaction at 4 months in relation to infant cognitive outcomes at one year, as measured by the Bayley Scales of Infant Development (Bayley, 2006). Although considerable literature documents associations of early mother-infant interaction with cognitive outcomes in the first and second year, there is relatively little work specifically examining the contributions of contingently coordinated mother-infant interaction to infant cognitive outcomes.

Cognitive development derives in part from genetic factors which govern brain development, but experiential factors are also critical to brain development and cognition (McV. Hunt, 1960). Several lines of evidence support the hypothesis that mother-infant interaction is one critical foundation of infant cognitive development. Studies of extreme caregiving deprivation in early life, such as may occur in institutional rearing, document negative effects on brain development and cognitive and physical health outcomes (Marshall & Fox, 2004; Rutter et al., 2004; Silvers et al., 2016; Tottenham et al., 2010). Moreover, variations in parental behavior influence infant brain development (Bernier et al., 2016; Bernier et al., 2019; Kok et al., 2015) in typical samples. For example, Bernier et al. (2016) documented that more maternal positive affect and less physical stimulation at 5 months predicted higher EEG power at 10 and 24 months. Finally, as we review below, considerable literature supports the claim that variations in mother-infant interaction, and especially variations in affective quality, predict infant cognitive outcomes. Here we are particularly interested in how variations in the *contingent* coordination of 4-month mother-infant interaction are associated with cognition at one year, a neglected topic. Contingency can be defined generally as a temporal relation between the occurrence of two or more events that involves sequential constraint (Tarabulsy et al., 1996; Watson, 1985).

1. Infant prediction of events

Infant ability to predict events is a key capacity that both underpins the capacity for contingent social coordination and supports the development of cognition. Haith et al. (1988) documented infant anticipatory visual prediction at infant age 3.5 months (see also DeCasper & Fifer, 1980; Watson, 1985, on prediction). Haith et al. (1988) videotaped one of the infant's eyes as the infant watched a series of slides that lit up in different predictable patterns. They showed that the eye of the infant anticipated the location of the next light in the predictable sequence. Using the example of infant auditory processing, and mismatch paradigms involving cortical event-related potential responses to unexpected auditory stimuli, Trainor (2012) argued that predictive information processing is a basic learning mechanism of the brain, available early in infant development (see also Gopnik & Wellman, 2012), and she characterized infants as sophisticated predictors, readily able to create expectations for example, of pitch, duration of sounds, and rhythmic sequences. For example, mismatch studies showed that 2-month infants detected gaps in tones of a few milliseconds (Trainor et al., 2003). Reeb-Sutherland et al. (2012) argued that early contingency learning is a basic mechanism underlying social and cognitive development, and they showed as early as the first month that contingency learning, in which infants learned to anticipate a puff of air to the eyes from a prior tone, predicted motor imitation and attention/ discrimination at 9 and 12 months, respectively.

Infant processing of probabilistic information and capacity to predict events allows for contingency perception in a social context, which facilitates cognitive processes such as attention, information processing, memory, and the procedural representation of interpersonal events (Fagen et al., 1984; Hay, 1997; Goldberg & Lewis, 1969; Trainor, 2012; Tronick, 1989). Temporal information occurring within and between individuals in a social interaction, such as mother-infant interaction, provides ongoing data upon which the infant can build predictions or expectancies of the moment-by-moment process of social interactions. Contingently coordinated behavior during face-to-face interaction is available at birth, even in infants born prematurely (Lavelli et al., 2022), and is robust by 4 months (Beebe et al., 1997; 2007; 2016; Tarabulsy et al., 1996). Further, mother and infant contingent processes during face-to-face interaction at 4 months are associated with cognitive and social outcomes at one year (Beebe et al., 2010; Jaffe et al., 2001).

Goldberg and Lewis (1969) laid the foundation for this line of reasoning with their "generalized expectancy" model. They argued that infant experiences of behavioral contingencies during social interactions is a key driver of cognitive development as infants learn through these contingent interactions that their behavior affects the environment. Moreover, Goldberg and Lewis pointed to work in adults suggesting that cortical changes are associated with the development of behavioral expectancies. Modern systems neuroscience also points to cortical, as well as subcortical and midbrain functions, that underpin sensory and reward prediction error processing and play a role in cognitive development (e.g., Corlett et al., 2022). Prior findings suggest that some similar processes govern infant prediction error processing, but much remains unknown (Berger & Posner, 2022).

2. Mother-infant interaction is associated with cognitive development

Extensive literature documents the importance of mother-infant interaction for infant cognitive development (which includes many different measures of infant cognition). Reviewing the literature in 1981, Belsky (1981) concluded that studies predicting infant intellectual development were surprisingly consistent in emphasizing the importance of attentive, warm, and non-restrictive maternal behaviors (see for example Crockenberg, 1983; Lewis & Coates, 1980; Estrada et al., 1987). Two decades later, Poehlmann and Fiese (2001) similarly characterized the literature as documenting that mutual attention, positive affect, engagement, and reciprocity facilitated infant cognitive development (see for example Hay & Kumar, 1995; Murray et al., 1996; NICHD Early Child Care Research Network, 1999; Smith et al., 2000). Poehlmann & Fiese's (2001) own study also showed that reciprocal, affectively positive engagement predicted higher Bayley Mental Development Index (MDI) scores, controlling for neonatal and maternal risks. Unlike most of this literature, Page et al. (2010), using global scales, documented that maternal encouraging, supportive verbal stimulation, but not maternal sensitivity, predicted higher infant Bayley MDI scores at approximately 9 months. More recent studies concur that a positive affective quality in early engagement promotes infant cognitive development (Sethna et al., 2017; Salley et al., 2016; White-Traut et al., 2018).

Sheinkopf et al. (2017) specifically tested the role of positive infant and maternal affect during 4-month face-to-face interaction in promoting infant cognitive development at 4 and 7 years, in a high-risk largely African American sample (examining the effects of prenatal cocaine/opiate exposure on child outcome in 1388 families). They used a second-by-second microanalysis coding approach (Infant Caregiver Engagement Phases, Weinberg & Tronick, 1998), and proportion of time spent in specific behaviors. When mothers used more positive social engagement and vocalizations, infants had higher IQ scores at 4.5 and 7 years. When infants used more positive affect (smiling, vocalizing, eye contact) interacting with an examiner (not the mother), infants had higher IQ scores at 4.5 years. Sheinkopf et al. (2017) suggested that infant experiences with positive face-to-face engagement might support positive infant learning experiences. Rocha et al. (2020) again noted that maternal responsiveness/sensitivity was the most consistent theme predicting infant language development. However, they commented that work on mother-infant interaction and developmental outcomes was limited and urged further research.

We now address studies which identified associations of mother-infant interaction with the Bayley Scales specifically. We limit our interest to mother-infant interaction in the first 6 months of life. Although these studies are sparse, they paved the way for our current interest. A partial review of these studies can be found in the Supplement (Table S1). An exemplary study in its time, Lewis and Coates (1980) coded many specific infant and maternal behaviors (coding in 10 s units), and their status as an initiation or a response, during mother-infant interaction at 3 months. They used a summary measure of higher maternal responsiveness, which was associated with higher concurrent Bayley MDI scores. Sethna et al. (2017), coding father-infant interaction at 3 months with Global Rating Scales, showed that greater paternal engagement/sensitivity and less controlling behavior predicted higher 24-month infant Bayley MDI scores. White-Traut (2018) coded a sample of 6-week premature infants and their high-risk mothers for specific infant and mother behaviors, such as mutual attention or positive affect (scaled as degree from 1–12), and they operationalized dyadic mutual responsiveness as high, medium, and low scores. They found that dyads with higher levels of dyadic mutual responsiveness had infants with better concurrent language and motor development on the Bayley III scales.

Studies by Feldman and colleagues stand out as exceptions in this literature for detailed coding of mother-infant interaction and assessments of contingency by time-series methods, predicting cognitive outcomes. For example, Feldman et al. (1996), coded face-to-face interaction at 3 and 9 months with Tronick's microanalysis method of Monadic Phases, used time-series methods, and assessed child cognitive outcomes at two years. They found that infant stochastic cyclicity at 3 months, defined as a nonrandom temporal process with some degree of predictability (measured by auto-correlation), was associated with general and verbal child IQ. Maternal synchrony with infant (infant behavior predicting maternal behavior) at 3 months was also associated with child visual IQ at two years. Infant stochastic process at 9 months was associated with general IQ, and maternal stochastic process at 9 months was associated with verbal IQ. They suggested that infant cognitive development may be facilitated by predictable (stochastic) infant processes because both predictability and flexibility (change) are involved in such processes. Their approach is similar to our own, in the inclusion of both self- and interactive processes, by time-series methods, as we describe below.

3. Critique of the literature

Despite extensive literature, most prior studies do not address the ways in which contingent coordination of mother-infant interaction may be associated with later infant cognitive outcomes. These studies tend to code specific behaviors, but then to create summary scores of frequency or degrees of a construct such as responsiveness or engagement. Studies which code behaviors by sampling relatively large units (such as 5 s or 10 s) will miss many relevant behaviors and will not capture the rapid, sequential flow of mother and infant behaviors which have durations of less than 0.5 s (Beebe, 1982; Stern, 1971). It is rare to code on a 1 s time-base (but see as exceptions Feldman et al., 1996; Salley et al., 2016; Sheinkopf et al., 2017), which tends to be the unit for time-series studies.

By collapsing behaviors into global scales, there is little specification of communication channel (modality) in this literature (see Sheinkopf et al.'s (2017) focus on affect as an exception). But specification of communication channels, such as gaze, facial affect, vocal affect, orientation, or touch, would allow us to understand more about how mother-infant communication might facilitate infant cognitive development. Patterns of contingent coordination differ as a function of the channel of communication examined. For example, in prior work on the origins of one-year attachment, the distinct communication modalities examined at 4 months each made unique contributions (Beebe et al., 2010).

The process of relating cannot be adequately captured by frequency measures, or degrees of a general concept. The process of relating is captured by the temporal dynamics of contingency approaches, such as that of time-series analysis, our approach. Although time-series approaches have been available since the 1980's (Gottman & Ringland, 1981; Cohn & Tronick, 1988), they are still not extensively utilized in the developmental literature (Cole, 2014; but see Feldman et al., 1996; Messinger et al., 2014). Whereas event-based approaches to contingency describe sequences of specific behaviors (maternal vocalization predicts infant smile), time-based (here "time-series") contingency approaches require continuous sampling of equal time intervals and describe the overall picture of the interaction.

In the study of face-to-face interaction, contingency measures using time-series approaches address self-processes as well as interactive processes. Self-processes tend to be overlooked, even in studies addressing contingent coordination in mother-infant interaction (see Beebe et al., 2016). Self-processes address probabilities of how the series of one person's behaviors unfolds in time; interactive processes address the probability that the series of behaviors of each partner predicts that of the other as they progress in time. Self-processes are critical to consider within the study of contingency for two reasons. First, self- and interactive processes affect one another (see Beebe et al., 2016). As Fogel (1993) noted, all behavior unfolds in the individual while at the same time continuously modifying and being modified by the changing behavior of the partner. Thus, self- and interactive contingency are both dyadic measures, in the sense that self- and interactive processes are assessed together: self-processes must be controlled when assessing interactive processes, and vice-versa. For example, to understand how partner A's behavior affects that of partner B, it is essential to control for how partner B's behavior is already affecting (predicting) herself. Second, in prior work we have shown that self-processes are a sensitive measure when investigating the associations of various risk pictures (maternal depression, anxiety; infant prematurity; mothers pregnant and widowed on 9/11: Beebe et al., 2008, 2010, 2011, 2020; Lavelli et al., 2022) with mother-infant interaction, and the associations of mother-infant interaction with social and cognitive outcomes (Beebe et al., 2010; Margolis et al., 2019).

In addition to these largely analytic considerations, in prior studies the samples range from middle-class Caucasian populations, particularly in the older studies (for example Crockenberg, 1983; NICHD, 1999); to other racial and ethnic groups in more recent studies (see Sheinkopf et al., 2017; Page et al., 2010). In the current study, we leverage data from an ongoing longitudinal prospective birth cohort that is composed of 90% Latina mothers and their infants, many of whom live in the context of economic disadvantage, who have been under-represented in previous studies. We thereby increase inclusivity in research.

4. Aims

We aim to increase our understanding of how contingent coordination during mother-infant face-to-face interaction at 4 months may facilitate cognition. We address many of the identified gaps in the literature by examining the ways in which the temporal dynamics of the contingent coordination of 4-month mother-infant interaction may be associated with the Bayley Scales of Infant Development at one year, a widely used, well-standardized measure of infant cognitive development which predicts later cognitive and social outcomes (NICHD Early Child Care Research Network, CRMC, NICHD, 2004). Our time-series approach to contingency captures infant capacity for anticipatory prediction and provides detailed specification of probabilistic self- and interactive processes (Beebe et al., 2016). We analyze multiple communication modalities (mother and infant gaze and facial affect, infant vocal affect, and maternal touch), coded on a one-second timebase and evaluate contingent self- and interactive processes in these modalities. Our study is conducted in a population-based sample of mostly Latina mothers living in the context of economic disadvantage, thereby increasing inclusivity in research.

5. Method

5.1. Participants

Participants were recruited from the prospective, longitudinal Fair Start birth cohort followed at the Columbia Center for Children's Environmental Health (CCCEH). The cohort recruits pregnant women receiving prenatal care at New York Presbyterian Hospital since 2013. Participants were women aged 18 + , speaking English or Spanish; 90% self-identified as Hispanic. Beginning in the spring of 2016, sequentially enrolled women were invited to participate in the current study assessing mother-infant interaction at infant age 4 months. The current study includes the first 100 mother-infant dyads who completed the 4-month mother-infant interaction visit and the 12-month visit to complete the Bayley Scales. The study was conducted according to guidelines in the Declaration of Helsinki, written informed consent was obtained from the parent before any data collection. The Institutional Review Boards at New York State Psychiatric Institute and Columbia University Medical Center approved all study procedures.

5.2. Power

If the interaction between mother-infant contingency and Bayley MDI scores explains greater than 0.13% of the unexplained variance (Cohen's $f2$=0.0013), we will have greater than 80% power with 5% type 1 error with $N = 100$. Thus, we will have more than enough power to detect small effect sizes (Cohen's $f2$=0.02) because of our multiple time-series data. We conducted this power analysis based on Cohen's f2 (Cohen, 1988). In estimating the degrees of freedom (df), to be conservative we used df= 500, much less than the minimum of df's (=3128) from the results of multi-level time-series analyses in our previous studies. Thus, given power (=0.70, 0.80, 0.90) and significance level of 0.05, df= 500, we computed Cohen's f2's, accordingly, as shown in Table 1.

Table 1
Power Analysis.

Cohen's f^2	Full sample (n = 100)
0.0010	70.00%
0.0013	80.00%
0.0018	90.00%
0.0054	99.99%

5.3. Procedure

5.3.1. Four-month mother-infant face-to-face interaction

Mother-infant face-to-face communication was evaluated at 4–5 months, a window of opportunity for assessing infant social development (Feldman, 2007). By this age, infants can sustain a face-to-face encounter, the regulation of states of arousal has matured, the capacity to engage and disengage visual attention has developed, and infant social capacities are increasing (Beebe et al., 2016; Tronick, 2007). Mothers were instructed to play with infants as they would at home, but without toys, for approximately 7 min. The infant was in an infant seat, mother seated opposite, as 2 video cameras (mounted on opposite walls) generated a split-screen view of upper torsos and hands.

5.3.2. 12-month cognitive assessment

The Bayley Scales of Infant Development, 3rd Edition (Bayley, 2006) was administered at one year in a lab setting by a trained research assistant. Quality control for administration and scoring was overseen by a licensed psychologist with expertise in developmental assessments. During the Bayley assessment, the infant completes a series of tasks and games that sample across the domains of language, motor, and visual-spatial cognitive abilities. The Mental Development Index (MDI) was used as the outcome measure. The MDI is a standard score with a mean of 100 (SD 15) and represents overall cognitive ability.

5.4. Video coding of behavior

Face-to-face communication is multi-modal, potentially generating multiple simultaneous signals which work in different ways (see Keller et al., 1999; Trevarthen, 1979; Van Egeren et al., 2001). But most research ignores this multi-modal reality, instead examining one or two modalities (Bahrick & Lickliter, 2002). Whereas we tend to see a molar "package" of all modalities operating at once in real time, second-by-second video microanalysis allows us to unpack different modalities. In this study we examined the modalities of mother and infant gaze, mother and infant facial affect, infant vocal affect, and mother touch. Mutual gaze is the foundation of the face-to-face encounter (Stern, 1971, 1985); degrees of negative to positive facial affect (including the highly evocative fully-opened "gape-smile") provide a leading index of the affective valence in each partner (Bigelow & DeCoste, 2003; Terrace et al., 2022); distinguishing infant facial affect and infant vocal affect allowed us to differentiate facial vs. vocal distress, for example; and mother touch, coded from affectionate to intrusive, is a central channel often neglected in studies of face-to-face communication (see Stepakoff & Beebe, 2023). Less affectionate maternal touch is associated with maternal depression (Beebe et al., 2008; Campbell & Cohn, 1991; Feldman et al., 2003; Field, 1995).

We coded the first 2.5 min of continuous uninterrupted videotaped play on a 1 s time-base, for mother and infant separately, by coders blind to Bayley scores. Samples of mother-infant face-to-face interaction of 2–3 min are stable, with robust session-to-session reliability, and standard in the literature (Beebe et al., 2010; Tronick, 2007). The communication modalities for infants (gaze, facial affect, and vocal affect) and mothers (gaze, facial affect, and touch) were coded with ordinal scales, ordered from high to low (except gaze on/off), as defined in Table 2 (for more extensive description of coding, see Beebe et al., 2010, Appendices A and B). Inter-rater reliability of coding (mean Cohen's Kappa) on 20% of the data follows: (a) *infants:* gaze .86, facial affect .84, vocal affect .88; (b) *mothers:* gaze .89, facial affect .86, touch .85.

Although 9 possible combinations of communication modalities could be examined (3 infant variables, 3 mother variables), we examined 7, as seen in Table 3. We omitted an analysis of mother gaze and infant facial affect reasoning that mothers will largely continue to gaze at infant's face irrespective of the particular infant facial affect; we omitted an analysis of mother touch and infant facial affect because it yielded relatively little in recent analyses (e.g. Beebe et al., 2020). We included an examination of infant intrapersonal cross-modal coordination of facial affect and vocal affect because this approach yielded important information in the study of mothers who were pregnant and widowed on 9/11 and their infants (Beebe et al., 2020), and because these two modalities were found to have a discrepant pattern in the origins of disorganized attachment (Beebe et al., 2010).

Table 2
Behaviors Coded.

Variable	Codes
Mother & Infant Gaze	on-off partner's face
Mother facial affect	mock surprise, smile 3, smile 2, smile 1, "oh" face, positive attention (interest), neutral[a], sympathetic "woe" face, negative face (frown/grimace/ tight compressed lips)
Infant facial affect	high positive smile, low positive smile, neutral/interest, mild negative (frown/grimace) pronounced negative (pre-cry/cry-face)
Infant vocal affect	high-positive, neutral-positive, no-voc, fuss/whimper, angry-protest, cry
Mother touch	affectionate (stroke, kiss), static (hold, provide finger for infant to hold), playful (tap, tickle), none, caregiver, jiggle/bounce, infant-directed oral touch, object-mediated, centripetal (body center: face, body, head), rough (scratch, push, pinch), high intensity/ intrusive (both rough touch and high intensity touch are considered intrusive)

Note
[b]The positive portion of the Mother Facial Affect Scale, mock surprise, smile 3, smile 2, smile 1, "oh" face, positive attention and neutral, was ordered by considering the degree of display of two dimensions, mouth-open and mouth-widen; see Beebe et al. (2010) Web Appendix A for full details of coding.

Table 3
Modality Pairings Examined.

Interpersonal Models		Infant Cross-Modal Model	
Infant	**Mother**	Infant	Infant
(1) Gaze	-Gaze	(8) Face	- VocA
(2) Gaze	-Face	(9) VocA	- Face
(3) Gaze	-Touch		
(4) Face	-Face		
(5) VocA	-Gaze		
(6) VocA	-Face		
(7) VocA	-Touch		

Note. VocA = vocal affect; face = facial affect

5.5. *Data analysis: time-series models*

Traditional time-series approaches model each dyad individually and enter model coefficients into analyses of variance. Multi-level time-series approaches (Chen & Cohen, 2006; Littell et al., 1996; Singer & Willett, 2003) model the group as a whole, creating estimates of fixed effects across the sample (group-level), and random effects (individual variation in those effects). Random effects include variation in the mean and the variance of the dependent variable across observations, variation in the linear change in the dependent variable over time, and between-dyad variation in the auto-regressive effect.

Advantages of multi-level modeling include more appropriate statistical assumptions; more accurate estimates of parameters by empirical Bayesian (maximum likelihood) techniques (rather than Ordinary Least Squares); simultaneous modeling of multiple time-series (in our case, self- and interactive contingency); and increased power. These models are designed to quantify patterns over time, here the course of behavior second-by-second, within individuals (self-contingency), and between two individuals (interactive contingency) (Beebe et al., 2020, 2007, 2016).

R-package 'lme4' was used to estimate random and fixed effects on the pattern of self- and self-with-other behavior over 150 s. We tested conditional associations of one-year Bayley MDI scores with 4-month mother and infant self- and interactive contingency, for 7 interpersonal modality-pairings, and two infant intrapersonal cross-modal pairings (see Table 3), controlling for infant gender and mother age (other covariates NS: maternal education, marital status, income-to-needs ratio, birth order). Beta values are standardized and thus represent effect sizes.

5.5.1. *Weighted-lag time-series analysis*

As in our prior work, primary analyses used weighted-lag models in time-series analyses of self- and interactive contingency, where estimated coefficients of one form of contingency control for the other (Beebe et al., 2010, 2016, 2020). Each model predicted one partner's self-and interactive contingency (see Supplement Tables S1a – S8d). Using a moving 4 s window, the prior 3 s of self and partner behavior, lags 1, 2 and 3 (L1, L2, L3), were used to predict t_0, the current second of behavior of one partner. All 3 prior seconds were condensed to one assessment ("weighted-lag") by weighting each prior second by its relative association with t_0. For each dependent variable, measures of prior self or partner behavior ("lagged variables") were computed as a weighted average of the prior 3 s, based on these models. The estimated coefficient for the effects of these lagged variables on t_0 over the duration of the interaction (150 s) indicates the level of self- or interactive contingency of one partner: the larger the coefficient, the stronger the contingency. The 4 s window size (3 prior seconds predict t_0) was based on prior work (Beebe et al., 2007, 2010, 2016). Typically, the prior 3 s accounted for these lagged effects on the subsequent behavior (t_0) (see Beebe et al., 2007, 2010. 2020). Using weighted lag multi-level time-series modeling, conditional effects of Bayley MDI (continuous scores) on the time-series data evaluated associations of 4-month self- and interactive contingencies with 12-month Bayley Scales.[1]

5.5.2. *Individual-seconds time-series models*

Individual-seconds time-series models supplemented the weighted lag approach (where again each model predicted one partner's self- and interactive contingency, and estimated coefficients of one form of contingency controlled for the other). These models identify specific patterns of behavioral predictors in L1, L2, and L3 that contribute to any significant group differences at t_0 (Beebe et al., 2018, 2020; Margolis et al., 2023). Three prior lags are evaluated for each second's association with the current moment (L1 → t_0; L2 → t_0, L3 → t_0) in one model, where each lag controls for the other two. A key difference between individual-seconds and weighted-lag models is that lags in the former are simply the values of the prior 1 s, 2 s, and 3 s, whereas lags in the latter are calculated in relation to t_0

[1] In the time-series modeling, we are predicting the current moment (t_0) using the past moment (3 prior seconds). This is an across-group analysis and it can stand on its own, without any other risk variable or outcome variable (see Beebe et al., 2016). However, to evaluate associations of other variables, such as infant attachment, or here, infant cognition, with the time-series, we use the other variable as a "conditional effect" on the time-series. Conditional effect here is a technical statistical term. The conditional effect in time-series modeling is a way of estimating an association between the contingency processes (by time-series) and some other variable, here the infant Bayley scores. We use the term "prediction" when we discuss the time-series modeling, as we evaluate the probability that prior behavior (of self) predicts current behavior of self (self-contingency) or partner (interactive contingency). We use the term "association" when addressing the relation between contingency processes and Bayley scores.

("weighted lag"). For simplicity of interpretation, the individual-seconds analysis does not accommodate the interaction terms of control variables with individual lags and Bayley scores. The weighted-lag approach detects differences using the prior 3 s collectively; the individual-seconds approach detects differences which are located in a particular second of the prior 3 s (Beebe et al., 2018) and thus applies a more precise lens to the microstructure of interaction differences that may be associated with Bayley MDI. Nevertheless, where findings of individual-seconds and weighted-lag analyses differ, we interpret findings of individual-seconds analyses with caution.

5.6. *Descriptive explication of weighted-lag models using individual-seconds time-series models: analysis of predicted values*

Multi-level time-series analyses identify differences in contingency levels associated with Bayley MDI scores but do not tell us where differences in specific behaviors lie. For example, lowered (more variable) infant gaze self-contingency may indicate greater likelihood of gaze-off to gaze-on, or the opposite. The meaning of the signs of self- and interactive contingency is often not immediately apparent and cannot necessarily be equated with optimal or nonoptimal patterns. Thus, post-hoc *descriptive explication* is required (see Supplemental Tables S1a – S8d: Tables Sc [predicted values for infants] and Tables Sd [predicted values for mothers]). For post-hoc descriptive explication, an *analysis of predicted values* was generated from the individual-seconds time-series models to explicate patterns that underlie significant group differences identified in weighted-lag models. No further significance testing is involved in this post-hoc analysis.

As noted above, to do weighted lag time-series models, we used the Bayley MDI scores as a continuous variable in evaluating conditional effects of Bayley MDI scores on contingencies. The predicted values approach (described below), however, requires a dichotomous measure of the Bayley scores. To do analysis of predicted values for the individual seconds time-series models, we cut the group into two by the top 25% quartile, with a cut-off of MDI = 116, generating a Higher-MDI Bayley group (MDI = 116 +) of $N = 28$, mean MDI = 122.36, (*SD* 4.36); and a Lower-MDI group of $N = 72$, mean MDI = 104.67 (*SD* 7.24).

Table 4
Demographic Factors in Higher-Bayley vs. Lower-Bayley MDI Groups.

Factor	Total (N = 100)	Lower-Bayley (n = 72)	Higher-Bayley (n = 28)	Chi-square	*p*-value
Maternal Ethnoracial				$\chi^2 = 1.92$	$p = .38$
Black/Latinx	5 (5.1%)	4 (5.7%)	1 (3.6%)		
Black/non-Latinx	4 (4.1%)	4 (5.7%)	0 (0.0%)		
Non-Black/Latinx	89 (90.8%)	62 (88.6%)	27 (96.4%)		
Maternal education				$\chi^2 = 6.50$	$p = .37$
Less than high school	2 (2.0%)	1 (1.4%)	1 (3.7%)		
Some high school	21 (21.2%)	17 (23.6%)	4 (14.8%)		
High school diploma	19 (19.2%)	13 (18.1%)	6 (22.2%)		
Some college	21 (21.2%)	18 (25.0%)	3 (11.1%)		
2 yr college degree	15 (15.2%)	11 (15.3%)	4 (14.8%)		
4 yr college degree	12 (12.1%)	6 (8.3%)	6 (22.2%)		
4 + yrs. of college	9 (9.1%)	6 (8.3%)	3 (11.1%)		
Marital status				$\chi^2 = 1.47$	$p = .83$
Divorced	6 (6.1%)	4 (5.6%)	2 (7.4%)		
Married	35 (35.4%)	24 (33.3%)	11 (40.7%)		
Never married	46 (46.5%)	35 (48.6%)	11 (40.7%)		
Partner_7yrs	10 (10.1%)	8 (11.1%)	2 (7.4%)		
Separated	2 (2.0%)	1 (1.4%)	1 (3.7%)		
Infant sex				$\chi^2 = .04$	$p = .84$
Male	48 (48%)	37 (51.4%)	15 (53.6%)		
Female	52 (52%)	35 (48.6%)	13 (46.4%)		
1st born/not 1st born				$\chi^2 = 3.65$	$p = .06$
First born	60 (60%)	39 (54.2%)	21 (75.0%)		
Not first born	40 (40%)	33 (45.8%)	7 (25.0%)		
	t-test				
Prenatal maternal Demoralization				$t = .81$	$p = .42$
N	98	71	27		
Mean (SD)		22.68 (15.22)	19.89 (15.06)		
Std. Error Mean		1.81	2.90		
Mean income to needs ratio				$t = -1.44$	$p = .15$
N	91	67	24		
Mean (SD)		7848.88 (5726.57)	10027.78 (7949.33)		
Std. Error Mean		699.61	1622.65		
Maternal age				$t = -1.70$	$p = .09$
N	100	72	28		
Mean (SD)		28.03(5.77)	30.21(5.83)		
Std. Error Mean		0.68	1.10		

Note. Higher vs. Lower Bayley was cut at the top 25%, Bayley MDI 116 (see method). Missing data: Ethnoracial (2), Maternal education (1), maternal demoralization (2), income to needs ratio (9).

5.6.1. Analysis of predicted values

Using the individual-seconds time-series models, we computed *predicted values* at t_0 for Higher-Bayley vs. Lower-Bayley groups for each significant finding. To identify sources of significant differences between groups, per modality-pairing, we generated every possible combination of the behavioral codes for mother at L1, L2, L3, and infant at L1, L2, and L3, in relation to the behavior predicted at t_0. The resulting value was the predicted level of the behavioral code at t_0 for ordinal behavioral scales, and the predicted probability of gaze-on at t_0 for gaze (binary). For each modality-pairing, the significant difference in predicted value of t_0 indicates that, although the Higher- (vs. Lower-) Bayley groups behaved in the same way over the prior 3 s, they behaved differently at t_0. We identified the absolute value of the difference of the predicted values for the two groups and ranked absolute differences from largest to smallest. To ascertain where groups most differed, we examined behavior combinations with the 10 highest differences in predicted value at t_0 (see Supplemental Tables S1a – S8d).

The conditional associations of 4-month self- and interactive contingency with one-year Bayley Mental Development Index (MDI) were tested in seven interpersonal communication-modality pairings and in two infant intrapersonal cross-modal models (of facial and vocal affect), as shown in Table 3. The Bayley MDI was evaluated as a continuous variable in primary models using the weighted lag approach, and as Higher- (vs. Lower-) Bayley groups in supplemental models using the individual seconds approach. In all time-series models we explored the following covariates: infant sex assigned at birth, maternal education, age, marital status, income-to-needs ratio (annual income divided by the number of people living in the home), and first-born vs. other-born. In final analyses we controlled only for those covariates that were significant: infant sex and maternal age. Tests of conditional effects of Bayley MDI on 4-month self- and interactive contingency used fixed effects (average effects across the sample). In addition to the intercept, fixed effects included: (1) lagged effects of self- and partner behavior (self- and interactive contingency); (2) differences in behaviors associated with groups; (3) differences in self- and interactive contingency associated with Bayley MDI. An example of the weighted lag time-series model equation can be found in Supplement II. The significance level was set at.05 (2-tailed). We had 100 dyads with 150 s observations per individual per modality to detect effects.

6. Results

6.1. Participant demographics

The demographics of the sample are shown in Table 4. The mean MDI score was higher than the normative sample ($M_{sample} = 109$ vs. $M_{normative} = 100$), with a smaller standard deviation than in the normative sample ($SD_{sample} = 10.32$ vs. $SD_{normative} = 15$). With the exception of trend level differences in primiparous status ($p = .056$) and maternal age ($p = .093$), the Higher-MDI vs. Lower-MDI Bayley groups did not differ in demographic characteristics (Table 4).

6.2. Associations between infant self- and interactive contingency and one-year Bayley MDI

6.2.1. Infant self-contingency

In *weighted lag models*, lower (more varying) infant self-contingency was associated with higher one-year Bayley MDI scores, in 4 (of 7) interpersonal models, and in 2 (of 2) infant intrapersonal cross-modal models, as summarized in Table 5: (1) *Infant facial affect self-contingency* (analyzed in relation to mother [M] facial affect), $\beta = -0.025$, $p = .001$ (Supplement Table S4a); (2) *Infant vocal affect self-contingency* (M gaze) $\beta = -0.027$, $p < .001$ (Table S5a); (3) *Infant vocal affect self-contingency* (M facial affect) $\beta = -0.025$, $p = .002$ (Table S6a); (4) *Infant vocal affect self-contingency* (M touch) $\beta = -0.027$, $p = .001$ (Table S7a). Infant self-contingency was also

Table 5
Weighted Lag Time-Series Models Summary: Associations of 4-Month Self- and Interactive Contingencies with 12-Month Bayley MDI Scores.

Interpersonal Models		Predicting Infant		Predicting Mother	
Infant	Mother	I→I	M→I	M→M	I→M
(1) Gaze	-Gaze				
(2) Gaze	-Face			↑	
(3) Gaze	-Touch			↑	
(4) Face	-Face	↓		↑	
(5) VocA	-Gaze	↓	↓		
(6) VocA	-Face	↓	↓	↑	
(7) VocA	-Touch	↓		↑	
(8, 9) Infant Cross-Modal Models		(8) Predicting I VocA		(9) Predicting I Facial Affect	
Infant Infant		V→V	F→V	F→F	V→F
VocA (V)	- Face (F)	↓			↓

Note.
1. Bayley Scales of Mental Development; MDI = Mental Development Index, treated as a continuous variable
1. I face = infant facial affect; IVocA = infant vocal affect
2. I → I = Infant Self-Contingency. M → I = Infant Interactive Contingency.
3. Entries = with higher Bayley MDI, 4-month contingency is increased ↑ or decreased ↓; see Supplement for full tables.

associated with higher one-year Bayley MDI scores in 2 (of 2) intrapersonal infant cross-modal models: (5) *Infant vocal affect self-contingency* (infant facial affect) $\beta = -0.023$, $p = .019$ (Table S8a); (6) *Infant facial affect self-contingency* (infant vocal affect) $\beta = -0.017$, $p = .030$ (Table S8a). *Individual seconds models* identified the same associations, as well as the specific prior seconds that accounted for significance, as summarized in Table 6.

Analysis of Predicted Values showed that, across the 2 significant infant facial affect self-contingency models, given both Higher-MDI and Lower-MDI group infants had negative facial affect in the prior 3 s, Higher-MDI infants became less negative in the current moment (Tables S4c, S8c). Across the 4 significant infant vocal affect self-contingency models, *Analysis of Predicted Values* showed that, given both Higher-MDI and Lower-MDI group infants had negative vocal affect in the prior 3 s, Higher-MDI infants became less negative in the current moment (Tables S5c, S6c, S7c, S8c).

6.3. Infant interactive contingency

In *weighted lag models*, lower (more variable) infant interactive contingency was associated with higher one-year Bayley MDI scores in 2 (of 7) interpersonal models, as summarized in Table 5: (1) *Infant interactive contingency: Mother gaze predicting infant vocal affect*: $\beta = -0.20$, $p = .004$ (Table S5a); (2) *Infant interactive contingency: Mother facial affect predicting infant vocal affect:* $\beta = -0.16$, $p = .010$ (Table S6a). Individual seconds models identified the same associations, as well as the specific prior seconds that accounted for significance.

Analysis of Predicted Values showed the following: for (1) *Mother gaze predicting infant vocal affect:* Given mothers of both Higher-MDI and Lower-MDI groups gazed away in the prior 3 s, Higher-MDI infants had less negative vocal affect in the current moment than Lower-MDI infants (Supplement Table 5c); (2) *Mother facial affect predicting infant vocal affect:* When mothers of both Higher-MDI and Lower-MDI groups had facial affect in the interest or mild negative range in the prior 3 s, Higher-MDI group infants had less negative vocal affect in the current moment (t_0) than Lower-MDI infants (Supplement Table 6c).

6.4. Associations between mother self- and interactive contingency and one-year Bayley MDI

6.4.1. Mother self-contingency

In *weighted lag models*, higher (less variable, more stable) mother self-contingency was associated with higher one-year Bayley MDI scores in 5 (of 7) models: (1) *Mother facial affect self-contingency* (infant gaze): $\beta = 0.024$, $p = .002$ (Table S2a); (2) *Mother touch self-contingency* (infant gaze): $\beta = 0.019$, $p = .017$ (Table S3a); (3) *Mother facial affect self-contingency* (infant facial affect), $\beta = 0.021$, $p = .011$ (Table S4a); (4) *Mother facial affect self-contingency* (infant vocal affect), $\beta = 0.024$, $p = .002$ (Table S6a); (5) *Mother touch self-contingency* (infant vocal affect), ($\beta = 0.017$, $p = .032$) (Table S7a). The individual seconds models did not generate significant results, although three showed trends, $p < .10$ (M touch [infant gaze], M facial affect [infant facial affect], and M touch [infant vocal affect]).

Analysis of Predicted Values showed the following: *(1) Mother facial affect self-contingency*: Across the 3 significant mother facial affect models, Analysis of Predicted Values (Tables S2d, S4d, S6d) showed that, given both Higher-MDI and Lower-MDI group mothers had positive facial affect in the prior 3 s, Higher-MDI mothers had more positive facial affect in the current moment; *(2) Mother touch self-contingency*: Across the 2 significant mother touch models, Analysis of Predicted Values (Tables S3d, S7d) showed that, given both Higher-MDI and Lower-MDI group mothers had negative touch patterns in the prior 3 s, Higher-MDI mothers were less positive in

Table 6
Summary of Individual Seconds Time-Series Models: Associations of 4-Month Contingency with 12-Month Bayley MDI Scores.

Modality Pairing	Mother-Infant Interpersonal Models											
	Infant						Mother					
	Infant → Infant			Mother → Infant			Mother → Mother			Infant → Mother		
	L_1	L_2	L_3	L_1	L_2	L_3	L_1	L_2	L_3	L_1	L_2	L_3
(1) Infant gaze – Mother gaze												↑
(2) Infant gaze – Mother face												
(3) Infant gaze – Mother touch												
(4) Infant face – Mother face	↓											
(5) Infant vocal affect – Mother gaze			↓		↓							
(6) Infant vocal affect – Mother face			↓	↓		↑						
(7) Infant vocal affect – Mother touch			↓									
(8, 9) Infant Cross-Modal Models	(8) Predicting Infant Vocal Affect						(9) Predicting Infant Facial Affect					
	L_1	L_2	L_3	L_1	L_2	L_3	L_1	L_2	L_3	L_1	L_2	L_3
	IVocA → IVocA			I face → IVocA			I face → I face			IVocA → I face		
(8, 9) Infant vocal affect – Infant face			↓				↓					

Note.
1. These multi-level individual seconds time-series models evaluate whether 4-month self- and interactive contingency are associated with Bayley MDI scores, treated as higher vs. lower scores
2. IVocA = infant vocal affect; I face = infant facial affect
3. Only significant findings are entered in the table.
4. Entries = contingency is increased ↑ or decreased ↓ with higher (vs. lower) Bayley MDI scores; see Supplement for full tables

touch patterns in the current moment.

6.4.2. Mother interactive contingency

There were no associations of mother interactive contingency with Bayley MDI in *weighted lag models*. There was one finding of mother interactive contingency associated with Bayley MDI in the individual seconds models: infant gaze predicting mother gaze, L3; $\beta = 0.308$, $p = .028$ (Table S1b).

Analysis of Predicted Values: Infant gaze predicting mother gaze showed that, given Higher-MDI and Lower-MDI group infants were gaze-on at L3, higher-MDI group mothers had a higher probability of being gaze-on in the current second (TablesS1d). Because this association appeared only in the individual seconds model, we interpret with caution.

Table 7 summarizes the results in verbal form.

7. Discussion

This study examined the temporal dynamics of self- and interactive contingency processes during mother-infant face-to-face interaction and their associations with higher (vs. lower) cognitive scores at one year, as measured by the Bayley Scales of Infant Development. Our time-series approach to measuring behavioral contingencies allows for detailed specification of self- and interactive processes. Our findings expand on a robust literature documenting the role of maternal affect in infant cognitive development. We showed that *self-contingency,* the probability that the individual's prior behavior predicts the individual's current behavior, was associated with infant cognition in 6 (of 9 possible) modality pairings in infant self-contingency findings, and 5 (of 7 possible) mother self-contingency findings; whereas interactive contingency between mother and infant was associated with infant cognition in 2 (of 7 possible) modality pairings. Specifically, more variable infant affective behavior was associated with higher cognitive performance scores at 1 year, reflecting greater modulation of negative affect; in contrast, more sustained maternal positive affect behavior was associated with higher cognitive performance scores at 1 year.

Although *interactive contingency* findings were sparse, they suggest that infants who were vocally less negative at moments when mothers were looking away or moving out of the positive range (into interest or mild negative facial affect) were more likely to have higher Bayley scores at 1 year. Our *multi-modal microanalysis approach* revealed modality-specific findings (e.g., findings largely in affect rather than touch or gaze), highlighting the benefit of specificity over global approaches. Thus, the time-series contingency approach identified potential behavioral pathways through which different affective states are generated, with associations to infant cognitive development, and with tangible implications for intervening in early caregiving to enhance child development.

7.1. Infant self-contingency

Infant self-contingency findings were remarkably robust, and all pointed to greater infant variability associated with more optimal cognition. Specifically, infant ability to move further out of negative affect at 4 months was associated with higher Bayley scores at one year. This pattern was evident in both infant facial affect and vocal affect. This finding may suggest that infant variable behavior is optimal for learning from the environment. It emphasizes the importance of the infant's own self-organizing process, particularly the ability to subtly shift distress, for emerging cognitive capacity. Our findings are similar to Feldman et al.'s (1996) findings that greater infant stochastic cyclicity, a similar time-series concept also measured by auto-correlation, but which includes a cycling (quasi-rhythmic) component, was associated with more optimal general and verbal child IQ at two years. However, our results document

Table 7

Verbal Summary: Contingency Patterns More Likely in Higher (vs. Lower) Bayley MDI Dyads.

Models (Modality)	Infant Self-Contingency	Infant Interactive Contingency	Mother Self-Contingency	Mother Interactive Contingency
I face → I face	Hi-MDI infants modulate negative face.			
I VocA → I VocA	Hi-MDI infants modulate negative VocA.			
M Gaze → I VocA		Given M looks away, Hi-MDI infants less negative VocA.		
M face → I VocA		Given M face interest/mild neg, Hi-MDI infants less negative VocA.		
M face → M face			Hi-MDI mothers sustain positive face.	
M Tch → M Tch			Hi-MDI mothers modulate negative touch patterns less.	
I Gaze → M Gaze				Hi-MDI mothers more likely to return infant's gaze (facilitate mutual gaze).

Note.

1. M face = mother facial affect; I face = infant facial affect; I VocA = infant vocal affect; M Tch = mother touch; Hi-MDI = higher-MDI; Lo-MDI = Lower-MDI.

2. Entries indicate patterns of contingency which were significantly more likely in hi-MDI dyads than lo-MDI dyads.

greater infant variability as more optimal, whereas Feldman's findings suggested that greater infant predictability may be optimal. We expand on Feldman's study by examining specific communication modalities and explicating the particular behavioral sequences involved in higher or lower self-contingency.

Our time-series finding that greater infant modulation of negative affect was associated with better cognitive performance is consistent with prior work showing that infant negative affect is associated with more problematic outcomes in development (NICHD Early Child Care Research Network, CRMC, NICHD, 2004), and that problems in early affect regulation may disrupt optimal cognitive development (Dodge, 1989; Baumeister et al., 2007; Richards, 2004; Scheibe & Blanchard-Fields, 2009). Moreover, our work expands on and refines prior findings which emphasize the role of positive engagement, dyadic mutuality, and maternal warmth and responsivity in infant cognitive development (see for example Belsky, 1981; Sethna et al., 2017; Poehlmann & Fiese, 2001; White-Traut et al., 2018). Our findings are also consistent with Sheinkopf et al. (2017) who emphasized the importance of the infant's own behavior in trajectories of cognitive development and hypothesized that the infant's own affective state at 4 months would predict verbal abilities. Notably, their finding differed from ours in important but complementary ways: infant positive rather than negative affect predicted cognitive outcomes, but with a novel partner rather than with the mother. Their measurement also differed: they examined frequency of behavior rather than contingency of behavior.

By using time-series data to understand contingencies, we showed that the infant's ability to modulate negative affect, rather than to sustain positive affect, was central to more optimal cognitive development. Our contingency approach allowed us to identify a potential behavioral mechanism through which the infant achieves the frequently reported finding of positive affect associated with more optimal cognitive development. That is, infants who had more variable behavioral streams of facial and vocal affect and moved further out of negative affect (from a more negative to a less negative affective level), rather than simply remaining in positive affect states, are likely to have more optimal cognitive development. Viewed within a developmental cognitive neuroscience perspective, such variability might increase the opportunity for sensory or reward prediction errors which in turn are associated with enhanced learning (Zhang et al., 2019).

7.2. Mother self-contingency

Mother self-contingency findings were also robust. We found that mothers who were more able to sustain positive affect during the face-to-face encounter had infants were went on to better cognitive performance at one year. Our findings are consistent with Feldman et al.'s (1996) report that higher (more predictable) maternal stochastic process (a measure of auto-correlation) predicted more optimal child verbal IQ at two years.

Our maternal self-contingency findings are also consistent with prior findings showing that maternal and dyadic positive engagement are associated with better cognitive development. Our finding is consistent, for example, with Sheinkopf et al. (2017), who showed that maternal positive affect and positive vocalization during face-to-face interaction at 4 months predicted child IQ at 4.5 and 7 years, and with Poehlman and Fiese (2001) who found that reciprocal, affectively positive, engaging interactions at 6 months predicted higher Bayley scores at one year. Moreover, maternal positive affect during mother-infant interaction was associated with greater changes in frontal power, reflecting more optimal brain development, from 5–24 months (Bernier et al., 2016).

Our findings expand on the role of maternal positive affect in infant cognitive development. Rather than relying on global measures of the positive quality of the mother-infant interaction, our time-series approach revealed the process through which associations between maternal affect and infant cognition may arise. Our findings suggest that maternal *ability to sustain* positive affect is a key aspect of this association. Such sustained maternal positive affect may serve as a positive frame for the infant. Within a developmental cognitive neuroscience framework, maternal sustained positive affect could be viewed as providing a form of reward for the infant; such ongoing opportunity for reward, regardless of the infant's own behavior, thus creates opportunity for the infant to experience positive reward prediction errors, which in turn may enhance learning (Zhang et al., 2019; Nixon & Tomaschek, 2021). Taken together our findings suggest that better cognitive performance is associated with the infant's greater ability to modulate negative affect, along with the mother's greater ability to sustain positive affect. Infant ability to modulate negative affect may be enhanced by sustained maternal positive affect; reciprocally, maternal positive affect may be enhanced (rewarded) by the infant's ability to modulate negative affect.

7.3. Interactive contingency

As we have previously documented (Beebe et al., 2016), for both infants and mothers, self-contingency organizes face-to-face interaction to a greater degree than interactive; the individual's behavior in the current moment is far more predictable from the individual's own prior behavior than from the partner's prior behavior. In the current study, only two findings (of 7 possible) emerged for *infant interactive contingency*, compared to 6 (of 9 possible) for infant self-contingency. Specifically, at moments when mothers were less available by looking away or moving out of the positive range (into interest/mild negative facial affect), infants who were vocally less negative were likely to have higher cognitive performance. Infant modulation of negative affect is thus a key process in both self and interactive contingency. Modulation of negative vocal affect may serve as a marker of a trajectory toward more optimal cognitive development.

For *mother interactive contingency*, of 7 possible findings, one emerged. When infants gazed at mothers' face, mothers of infants who were likely to have better cognitive performance were more likely to gaze back, increasing the likelihood of mutual gaze. Because this finding was identified only in the individual seconds time-series model, we interpret with caution. It is interesting that maternal contingent interactive coordination was identified through gaze, rather than affect, as suggested by the literature.

7.4. Multimodal approach

Facial and vocal affect were the main communication channels in which we detected associations between behavioral contingencies and cognitive performance. Every model testing self-contingency of affect was significant. For infants, of 6 possible time-series models containing infant facial or vocal affect, all 6 revealed findings. For mothers, of 3 possible models containing facial affect, all 3 revealed findings. Nevertheless, each communication modality revealed different information, and differences within a communication modality also emerged. (a) Facial affect functioned differently for mothers and infants: modulation of negative affect for infants, but sustaining positive affect for mothers, was associated with more optimal infant cognitive development. (b) Infant facial and vocal affect shared the function of modulating negative affect in self-contingency findings, but only infant vocal affect played a role in infant interactive contingency, the modulation of negative vocal affect at moments when mothers were less visually or affectively available. (c) The role of gaze was less evident in our findings, appearing only in interactive regulation patterns. For infants likely to have higher cognitive performance, mother gaze away was followed by infant modulation of negative vocal affect; when infants looked, their mothers were more likely to return the gaze. (d) Mother touch was the one modality in which mothers of infants on the way to higher cognitive performance showed less optimal patterns. Both groups of mothers modulated negative touch patterns, but mothers of higher MDI infants modulated negative touch somewhat less. This maternal pattern occurred in the context of greater capacity to regulate negative affect in higher MDI infants.

More optimal infant cognitive development seems to depend more on mothers sustaining positive facial affect rather than modulating negative touch patterns. We note that all these nuances are missed with approaches that do not parse communication channels. They are also missed in microanalysis approaches which combine multiple modalities into an engagement scale, so that the contribution of individual modalities is lost.

7.5. Behavioral mechanism

We suggest that infant ability to predict events and contingency learning is a useful way of conceptualizing the behavioral mechanism of these findings. The time-series approach utilized in our analyses uses a predictive (probabilistic) model, evaluating the likelihood that prior behavior predicts current behavior. Infants have remarkable capacities to detect regularities in events, to perceive contingencies, and to anticipate events that are likely to occur (Haith, Hazan, & Goodman, 1988; Tarabulsy, Tessier, & Kappas, 1996). Infant ability to detect contingency and predict events acts as a powerful learning mechanism that allows infants to develop expectancies of their own and the partner's behavior and to coordinate their own behavior accordingly.

7.6. Alternative perspectives: executive function and emotion regulation

Increasingly, the literature favors an integrated view of cognitive and affective processes in early infant development (Rochat, 2001; Wolfe & Bell, 2023). Our 4-month infant self-contingency results can be seen as precursors of what may later be termed executive function as well as emotion regulation. According to Bell and Meza (2020, p. 568), in infancy, "foundational executive function skills are inhibitory control, updating, and shifting." We suggest that our 4-month self-contingency pattern of greater variability, such that infants are more likely to modulate negative affect, can be seen as including both shifting processes, that is shifting from more negative to less negative facial and/or vocal affect; as well as inhibitory processes, such that more negative affect is inhibited in favor of less negative affect. But, our 4 month infant self-contingency results can equally well be seen as precursors of what may be termed emotion regulation, which, according to Cole et al. (2004, p. 320), "refers to changes associated with activated emotions." These authors distinguish between emotion as *regulating*, and emotion as *regulated* (Cole et al., 2004). Our findings fit their concept of emotion as regulated, for example, changes in "emotion valence or intensity" (Cole et al., 2004 p. 320). Our findings of greater infant likelihood of change from more negative to less negative facial and/or vocal affect indicate a change in emotion intensity. Understanding precursors of executive function and emotion regulation in early infancy requires a consideration of the interactive context in which these functions develop. Our finding of infant of modulation of negative affect facilitating higher (vs. lower) infant cognitive scores at one year exists in the context of greater maternal stability of positive facial affect. We argue that greater maternal positive facial affect stability may facilitate emerging infant processes of both executive function and emotion regulation, and vice-versa. Our findings provide an illustration of ways in which infant social and cognitive processes are intimately intertwined.

7.7. Limitations

Our study has some limitations. Although the findings of this study would need to be replicated to be able to generalize, our use of a community sample increases the generalizability of our findings. Future studies could examine samples weighted for lower cognition e.g., with genetic disorders associated with lower infant cognitive ability. We also have a relatively small sample from a single geographical location, although our sample represents an understudied group of mothers. Further, racial and ethnic disparities in performance on the Bayley (Duncan et al., 2012) limit its utility with understudied groups. Nonetheless, in our sample the mean score was two thirds of a standard deviation higher than the population mean**.** Such findings are notable in that socioeconomically disadvantaged youth have been characterized as being at risk for less optimal cognitive outcomes (Noble & Giebler, 2020), but our results suggest the opposite in this sample. Moreover, the Bayley is not the most sensitive instrument to understand neurocognitive development (Brito et al., 2019) and future studies should use more nuanced measures to examine associations between contingently coordinated behavior and cognition.

8. Conclusion

Our findings demonstrate the robust ways in which infant and mother self-contingency, the second-by-second probability that prior behavior predicts future behavior, were associated with infant cognitive development. We identified patterns of interaction, particularly patterns of self-contingency, that facilitated infant cognitive development, not identified in prior studies. Mother and infant affect was the central communication channel that identified our findings. However, each communication modality played a unique role in associations with cognitive performance. Self-contingency findings showed that more varying infant behavior was optimal for infant cognitive performance at one year, revealing greater modulation of negative affect; whereas more stable maternal behavior was optimal for infant cognitive performance at one year, revealing patterns of greater likelihood of sustaining positive facial affect. Our infant self-contingency findings identify a potential behavioral mechanism with which infants may achieve more positive affect, that is, the ability to move from more negative to less negative facial and vocal affect, rather than simply remaining in positive affect states. We suggest that infant ability to modulate negative affect, and maternal ability to sustain positive affect, may be mutually reinforcing, together creating a dyadic climate that is associated with more optimal infant cognitive performance. We propose that the communication patterns documented potentially organize infants' developing procedural expectancies of the ways that interactions proceed, affecting the trajectory of cognitive development.

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Author statement

We declare that this manuscript is original, has not been published before and is not currently being considered for publication elsewhere. We confirm that the manuscript has been read and approved by all named authors and that there are no other persons who satisfied the criteria for authorship but are not listed.

We further confirm that the order of authors listed in the manuscript has been approved by all of us. We understand that the Corresponding Author is the sole contact for the Editorial process. He/she is responsible for communicating with the other authors about progress, submissions of revisions and final approval of proofs.

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Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request once the core data analysis goals of the R01 are accomplished.

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.infbeh.2023.101920.

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