Running Head: DYNAMIC AFFECT COUPLING BETWEEN INFANTS AND PARENTS

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Dynamic Infant-Parent Affect Coupling during the Face-to-Face/Still-Face

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Abstract

We examined dynamic infant-parent affect coupling using the Face-to-Face/Still-Face (FFSF). The sample included 20 infants whose older siblings had been diagnosed with Autism Spectrum Disorders (ASD-sibs), and 18 infants with comparison siblings (COMP-sibs). A series of mixed effects bivariate autoregressive models was used to represent the self-regulation and interactive dynamics of infants and parents during the FFSF. Significant bidirectional affective coupling was found between infants and parents, with infant-to-parent coupling being more prominent than parent-to-infant coupling. Further analysis of within-dyad dynamics revealed ongoing changes in concurrent infant-parent linkages both within and between different FFSF episodes. The importance of considering both inter- and intra-dyad differences is discussed.

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The study of dyadic interaction can be construed in dynamic terms (Fogel & Thelen, 1987; Smith & Thelen, 1993). Members of a dyad are intertwined: they act and react to each other's behaviors and emotions. The cascading effects of such interactions can often lead to highly unpredictable outcomes, triggered both by the dynamics inherent to each dyadic member, as well as the interdependencies between the past histories and the future responses of the two dyad members. Likewise, subtle between-dyad differences can manifest themselves in whether and how dyad members are "coupled" to one another over time.

Dynamic systems-based concepts have played a prominent role in contemporary studies of dyadic relationships (e.g., Boker & Laurenceau, 2006; Felmlee & Greenberg, 1999; Gottman, Murray, Swanson, Tyson & Swanson, 2002; Levenson & Gottman, 1983) and the study of affect (Bisconti, Bergeman, & Boker, 2004; Chow, Nesselroade, Shifren, & McArdle, 2004; Fredrickson & Losada, 2005). Larsen's (2000) homeostatic model of mood regulation, for instance, conceptualizes mood regulation as an ongoing process during which an individual attempts to minimize the discrepancies between his/her current mood states and an individualized set point. Chow, Ram, Boker, Fujita and Clore (2005) formulated this theoretical model of a "mood thermostat" as a differential equation whose dynamics are governed by two key parameters: a frequency parameter that dictates how rapidly the system shows cyclic fluctuations (i.e., affect lability), and a damping parameter that governs how promptly the system returns to (or diverges from) its set point (i.e., affect adaptivity) following a perturbation.

The damped thermostat model provides one possible way of testing dynamic notions of mood regulation within the context of a differential equation model. In instances involving dyadic data, complication arises because the affective equilibrium of the dyad is defined jointly by the emotional ebbs and flows of the two dyad members. A bivariate model is thus needed to accommodate both the self-regulation as well as the interactive dynamics of the dyad members as two "coupled thermostats". To provide a more concrete analogy of how parents and infants might act and react to one another in the manner of two coupled thermostats, consider the two dyad members acting as "partners" on a three-legged race. If one party is making rapid strides (e.g., manifesting rapid emotional fluctuations), the other party may have to adapt accordingly and adopt a faster pace, or force the partner to slow down his/her pace. Whether one dyad member adapts to, or actively alters the pace of the other dyad member may depend on which partner is leading. Alternatively, the two dyad members may act as two "independent thermostats" that fluctuate around their respective equilibrium points irrespective of the dynamics of one another.

The key objective of the present article is to provide guidelines on how dynamic systems-inspired models can be used to represent parent-infant dyads as "coupled thermostats" and test specific hypotheses concerning (1) general lead-lag relationships between parents and infants during active interaction, (2) between-dyad differences in interactive dynamics and (3) within-dyad changes in interactive dynamics. These modeling aims are examined using dyadic data collected during the Face-to-Face/Still-Face (FFSF) procedure.

During the FFSF, the parent is instructed to engage in play with the infant in the Face-to-Face (FF) episode, to then, cease play and holds a motionless expression during the Still-Face (SF) episode, and to resume playing with the infant in the Reunion (RE) episode (Tronick, Adamson, Wise, & Brazelton, 1978). The decline in positive affect and increase in negative affect during the SF episode—often known as the still-face effect—have been replicated across multiple studies (Adamson & Frick, 2003; Mesman, Van IJzendoorn, & Bakermans-Kranenburg, in press; Tronick & Cohn, 1989; Weinberg & Tronick, 1996; Tronick, Messinger et al., 2005; Yale, Messinger, & Cobo-Lewis, 2003). The stress caused by the SF manipulation and the reconciliations during the reunion episode provide a direct opportunity for assessing between- and within-dyad changes in affective regulatory dynamics. From a between-dyad differences standpoint, we seek to evaluate differences in infant-parent interactive dynamics related to infant gender and to heightened risks for autism spectrum disorders. From a within-dyad standpoint, we present a model for testing within-dyad variability in parent-infant associations that addresses whether, and in what ways, parent-infant associations change over time within and between the FFSF episodes.

Relative Dominance of Parent-to-infant and Infant-to-parent Influences

In studies of parent-child interaction, researchers have been concerned with interactive influence and with synchrony (Brazelton, Kozlowski, & Main, 1974). Interactive influence involves the impact of infant-to-parent (parental responsivity) and parent-to-infant (infant responsivity) influence. Higher levels of parental responsivity are associated with a wide variety of developmental outcomes, including the development of secure infant attachment to the parent (Isabella & Belsky, 1991; Jaffe, Beebe, Feldstein, Crown, & Jasnow, 2001), conscience-based rule-following in the child (Kochanska, Forman, & Coy, 1999), the infant's understanding of their developing emotional expressions (Stern, 1985; Tronick, 1989), as well as linguistic and cognitive development (Feldman & Greenbaum, 1997; Feldman, Greenbaum, Yirmiya, & Mayes, 1996; Landry, Smith, Miller-Loncar, & Swank, 1997). In a similar vein, infants have also been postulated to show a developmental tendency to adapt to changes in their parents' behavioral and emotional patterns (Ainsworth, Blehar, Waters, & Walls, 1978; Brazelton et al., 1974; Tronick & Gianino, 1986).

Infant-to-parent influences can exist simultaneously with parent-to-infant influences, producing bi-directional interactions. Bi-directional influence is thought to be the basis of fundamental social competencies such as turn-taking (Cohn & Tronick, 1988; Kaye & Fogel, 1980), and the development of secure attachments (Jaffe, Beebe, Feldstein, Crown, & Jasnow, 2001). Despite empirical evidence indicating the bidrectional nature of parent-infant influences, even research which has addressed the relative importance of parent and infant in interaction has typically done so by categorizing individual dyads as to the presence or predominance of infant-to-parent and parent-to-infant influence (Cohn & Tronick, 1988; Feldman, et al., 1996; Yirmiya et al., 1996). There is some evidence, however, that infant-to-parent interactive influence is an earlier developmental achievement than parent-to-infant influence (Feldman, Greenbaum, & Yirmiya, 1999), thus underscoring its potential importance to interaction (Beebe, Jaffe, Buck, Chen, Cohen, & Blatt, 2007). The present article provides a concrete methodological example of how a bivariate autoregressive (AR) model can be used to identify the nature and directionality of parent-infant coupling in dyadic interaction. We hypothesized the existence of bidirectional infant-parent interactive influence that would be dominated by infant-to-parent influence.

Between-Dyad Differences in Interactive Dynamics

Autism spectrum disorders (ASDs). Autism Spectrum Disorders (ASDs) are neurodevelopmental disorders characterized by a spectrum of impairments in social functioning and communication (Landa, Holman, & Garret-Mayer, 2007; Mundy & Hogan, 1994). ASDs are highly heritable and may mark the diagnosable end of a genetically-linked spectrum of difficulties (Szatmari et al., 2000). Compared to infant siblings of typically developing controls, infant siblings (as well as other first-degree relatives) of individuals with an ASD (ASD-sibs) are at increased risk for milder deficits in one or more of the three areas that are impaired in autism:

social responsiveness, communication, and limited interests/stereotyped behavior (Yirmiya et al., 2006; Merin, Young, Ozonoff, & Rogers, 2007; Cassel et al., 2007; Pickles et al., 2000).

In a study involving 12-month-olds, ASD-sibs who later showed autistic symptomatology were characterized by deficits in social smiling and decreased manifestations of positive emotions (Zwaigenbaum et al., 2005). Infant ASD-sibs smiled for a smaller proportion of the FFSF (Cassel et al., 2007), showed an increased tendency for neutral affect and were less upset by the still-face manipulation relative to comparison siblings (COMP-sibs; Yirmiya et al., 2006). Merin et al. (2007), however, did not find differences in emotional expressivity between ASD-sibs and COMP-sibs during a FFSF study with a brief still-face episode.

We seek to further clarify the differences between ASD-sibs and COMP-sibs (and lack thereof) in establishing and maintaining interactive synchrony with their parents from a dynamic standpoint. Based on previous evidence for subtle deficits in interactive influence in dyads composed of a parent and an ASD-sib, we use a mixed effects bivariate AR model to examine differences in interactive influence parameters due to the presence of ASD-sibs. Based on Yirmiya et al.'s (2006) finding that the parents of ASD-siblings showed lower levels of responsivity to their infants in the FFSF than comparison parents, we expected reduced levels of infant-to-mother influence in ASD-sib dyads relative to comparison dyads. We also predicted reduced levels of ASD-sib infant responsiveness to parental influence, based on consistent reports of ASD-sibs' difficulty in responding appropriately to others (Dawson, Meltzoff, Osterling, Rinaldi, & Brown, 1998; Landry & Bryson, 2004; Mundy, 2003). In sum, relative to dyads composed of COMP-sibs, we expected ASD-sib dyads to show lower levels of parent-to-infant as well as infant-to-parent coupling in the interactive episodes of the FFSF (FF and RE).

Gender. Although Weinberg, et al. (1999) reported that male infants had more difficulty than female infants in maintaining affective regulation across the FFSF paradigm, the literature as a whole suggests no specific directional hypotheses concerning the effect of gender on interactive influence (Carter et al., 1990; Haley & Stansbury, 2003; Stoller & Field, 1982). The higher prevalence of ASDs in males than in females (Fombonne, 1999; Honda, Shimizu, Imai, & Nitto, 2005; Yeargin-Allsopp et al., 2003), however, suggest the need to consider gender, and the interaction of gender and risk status, as predictors of between-dyad differences in interactive dynamics.

Within-Dyad Changes in Parent-Infant Synchrony

Several studies in the past decade have documented meaningful within-person variability in constructs—including world views and perceived control—that were traditionally construed as relatively stable or “static”, (Eizenman, Nesselroade, Featherman, & Rowe, 1997; Kim, Nesselroade, & Featherman, 2001). In the study of affect, within–person day-to-day variations in emotions and cardiovascular measures have been reported to constitute stable between–person differences that are different from interindividual differences in affect intensity (Eid & Diener, 1999; Larsen, 1987; Ong & Allaire, 2005).

Parent-infant interaction involves matches and mismatches in affective engagement. Given that infant and mother interactive behaviors are not deterministic but, rather, encapsulate the stochastic influence of the two partners (Cohn & Tronick, 1988; Fogel, 1988), within-dyad variability in synchrony constitutes an important aspect of interaction. Previous investigators of the FFSF were often interested in capturing a summary measure of infant-parent dynamics that were assumed to be stable over the course of an interaction. In empirical data that span longer time scales, however, the assumption of stationarity[1] is often violated (see e.g. Lavie, 1977;

Tarvainen, Georgiadis, Ranta-aho & Karjalainen, 2006; Weber, Molenaar & Van der Molen, 1992). Studies of adult dyadic interaction suggest that interpersonal dynamics can change in critical ways even during a brief episode of interaction (e.g., due to turn-taking behavior; Boker, Xu, Rotondo & King, 2002; Newtson, 1993). To our knowledge, no previous study in the affect or developmental literature has actively pursued evidence for time-varying changes in infant-parent affective associations.

We present a novel model—one that combines an autoregressive model and a stochastic regression model (see Shumway & Stoffer, 2000)—to explore the existence of within-dyad changes in interactive dynamics during the FFSF. The regression model is "stochastic" because a time-varying regression coefficient is included in the model to capture whether, and in what ways, parent-infant synchrony changes within dyads over the course of each FFSF episode.

Over all, we expected group level deficits in interactive coupling and responsivity to become accentuated during and after the perturbation in interaction caused by the SF. Based on previous reports of ASD-sibs' consistent difficulty in responding appropriately to others (Dawson, Meltzoff, Osterling, Rinaldi, & Brown, 1998; Landry & Bryson, 2004; Mundy, 2003), we predicted reduced overall variability in ASD-sib's emotional fluctuations during the SF and RE as compared to COMP-sibs. We had no specific hypotheses regarding ASD-sib related differences in changing levels of interactive coupling within time. Although ASD-sib dyads might be expected to show higher levels of variability in their responsiveness in time, such variability might also index adaptive flexibility, which was depressed in the ASD-sib dyads.

Method

Participants

Infant-parent dyads in this study were part of a longitudinal study investigating the social, emotional, and cognitive development of ASD-sibs and COMP-sibs in the first three years of life. Outcome data are not yet available for these infants. Cassel et al. (2007) examined mean levels of smiles and cry-faces in a sample that included 82% (31 out of 38) of the infants who are part of the current mean-free analysis of rated emotional valence. Infants were included in this sample if they participated in a six-month assessment, were at least 36 weeks gestation at birth, and had a birthweight above 2500g. The COMP-sibs were infants whose older sibling(s) had not been diagnosed with an ASD and showed no evidence of heightened ASD symptomatology. In contrast, ASD-sibs had at least one sibling who was diagnosed with Autism, Asperger's Disorder, or Pervasive Developmental Disorder – Not Otherwise Specified (PDD-NOS). Due to persistent distress, data collection was terminated for one of the ASD-sibs (male) during the FFSF. Excluding the data from this dyad yielded a final sample of $N = 38$ dyads, with 18 COMP-sibs and 20 ASD-sibs.

The sample consisted of 36 infant-mother dyads and two infant-father dyads.[2] The mean age of the 38 infants at the six-month assessment was 6.1 months ($SD = .3$; range 5.1 to 6.9 months). Mean parent age in years at the six-month FFSF assessment was 36.7 ($SD = 4.8$). A total of 57.9% of the mothers and 42.1% of the fathers reported earning an advanced or professional degree and another 21.1% of mothers and 31.6% of fathers reported completed a 4-year college degree. There were no differences in infant age, parent age, education or family income between the ASD-sibs and the COMP-sibs.

Measures

We used the Continuous Measurement Software[3] (CMS) to obtain ratings for every frame of the video upon playback of the video file. The CMS was developed to enable the presentation of video files to human raters in randomized sequence and simultaneous recording of viewers' ratings of the video files (Messinger, Cassel, Acosta, Ambadar, & Cohn, 2008). Raters were asked to use a joystick to move the cursor up or down along a graduated color bar adjoining the right margin of the frame in which the video was being displayed.[4] A screenshot of the user interface to which the raters were exposed is shown in Figure 1. The raw ratings generated by the CMS ranged from -400 (i.e., most negative) to +400 (most positive). We defined emotional valence as a continuous, unidimensional construct with positive and negative as anchors. This relatively simple measurement scale was used to facilitate continuous measurements of emotional valence with minimal rater delays[5].

Procedure

In the FFSF protocol (Tronick et al., 1978; Tronick & Cohn, 1989), parents were asked to play with their baby without toys for three minutes (Face-to-Face episode, FF), stop playing and maintain a still face with no emotional expression for two minutes (Still-Face, SF), and resume play for another three minutes (Reunion episode, RE). During all three episodes, infants were placed in an elevated car seat and their parents were positioned on a small chair directly opposed to them. Separate video cameras were used to record the face and upper body of the infant and of the parent. The video signals were synchronized with respect to a common time code and exported to separate digital video files for rating.

Descriptions of Raters

Ratings of the 38 dyads were completed by 188 non-expert student raters at a large urban university in the Southeast in fulfillment of the research component of an introductory psychology course. The raters were non-experts in that they had no specialized training in coding emotion. A given rater rated either infants or parents (not both). The mean age of raters was

19.6 years (SD = 2.5). The raters' ethnicity was 54% Caucasian, 24% Hispanic, 7% Asian, and 15% Black/Other; 28% were male.

Each non-expert rated a group of 8 infants (or parents) containing separate video clips for each episode of the FFSF (i.e., FF, SF, & RE). Clips were rated in a randomized order and raters proceeded from one video clip to the next at their own pace. Generalizability Theory (GT) analyses reported elsewhere (Baker, Haltigan, Brewster, Jaccard, & Messinger, 2009) indicated strong consistency in the non-expert ratings provided by the student raters. For cross-validation purposes, a randomly selected subset of the dyads was subjected to further ratings by parents who also participated in the FFSF. Parent raters are, arguably, more experienced in coding infants' emotions than the student raters. Parent ratings were available for 7 of the 33 (i.e., 35%) dyads. The correlations between these ratings were .76 (FF), .91 (SF) and .91 (RE) for the infants, and .83 (FF), .84 (SF) and .92 (RE) for the parents. The high correlations between student and parent ratings provided further support for the use of these non-expert ratings in our subsequent analyses.

Data Preprocessing

We took several data processing steps prior to model fitting to minimize preexisting between-rater differences in ratings. First, we discarded the first 10 seconds of ratings from all raters to minimize the initial delays manifested by some raters as they were "warming up" to the rating protocol. Second, we removed spurious trends—including linear and quadratic trends, as well as other gradual (e.g., exponential) upward/downward shifts in ratings—by applying a Loess smoother and retaining the residuals for further analyses.

Third, for each parent/infant, we derived a time series of mean ratings by first standardizing each rater's ratings for that participant (over time) separately and then averaging these standardized ratings across all raters. The time series of mean ratings for each infant (and parent) was then restandardized over time. Thus, all dyads and all episodes were characterized by the same magnitude of within-person standard deviation (= 1.0) over time. This meant that any between-dyad or between-episode differences associated with our subsequent analyses were not due to differences in affective levels or affective variability across dyads or episodes.

Model Descriptions

Testing lead-lag relationships between parents and infants. We first used a bivariate AR models with no dyad-level covariate to address the first modeling aim, namely, to determine the general lead-lag relationships between parents and infants in interactive dynamics. The corresponding vector AR (VAR) model is expressed as

$$\begin{aligned}
Infant_{ikt} &= \phi_{1,infant} Infant_{ik,t-1} + \phi_{2,infant} Infant_{ik,t-2} + \phi_{parent->infant,i} Parent_{ik,t-1} + e_{infant,ikt} \\
Parent_{ikt} &= \phi_{1,parent} Parent_{ik,t-1} + \phi_{2,parent} Parent_{ik,t-2} + \phi_{infant->parent,i} Infant_{ik,t-1} + e_{parent,ikt} \\
\phi_{parent->infant,ik} &= b_0 + b_1 SFvsFF/RE_{ik} + b_2 FTFvsRE_{ik} + u_{\phi_{parent->infant_{ik}}} \\
\phi_{infant->parent,ik} &= c_0 + c_1 SFvsFF/RE_{ik} + c_2 FTFvsRE_{ik} + u_{\phi_{infant->parent_{ik}}},
\end{aligned}$$

$$\begin{bmatrix} u_{\phi_{parent->infant_{ik}}} & u_{\phi_{infant->parent_{ik}}} \end{bmatrix} \sim N\left(\begin{bmatrix} 0 \\ 0 \end{bmatrix}, \begin{bmatrix} \sigma^2_{u_{parent->infant}} & \\ 0 & \sigma^2_{u_{infant->parent}} \end{bmatrix} \right), \quad (1)$$

$$\begin{bmatrix} e_{infant,ikt} & e_{parent,ikt} \end{bmatrix} \sim N\left(\begin{bmatrix} 0 \\ 0 \end{bmatrix}, \begin{bmatrix} \sigma^2_{e_{infant}} & \\ 0 & \sigma^2_{e_{parent}} \end{bmatrix} \right)$$

where $Infant_{ikt}$ represents the emotional valence of the infant in dyad *i* during FFSF episode *k* at time *t*, $Parent_{ikt}$ represents the emotional valence of the parent in dyad *i* in episode *k* at time *t*, *SFvsFF/RE* and *FFvsRE* are a set of contrast codes used to indicate the different FFSF episodes. *SFvsFF/RE* was constructed to compare the SF to the FF and RE conditions combined (*SFvsFF/RE* = 1 for SF, -1/2 for FF and -1/2 for RE) and *FFvsRE* was used to compare the FF to the RE condition (*FFvsRE* = 0 for SF, 1 for FF and -1 for RE). The parameters $\phi_{1,infant}$ and $\phi_{1,parent}$ represent the group-based AR(1) parameter for infants and parents, respectively, whereas $\phi_{2,infant}$ and $\phi_{2,parent}$ denote the group-based AR(2) parameter for infants and parents, respectively. The AR parameters capture the lagged effects of a dyad member's emotional valence from *t*-1 and *t*-2 on the dyad member's current emotional valence. $\phi_{parent->infant,ik}$ and $\phi_{infant->parent,ik}$ are lag-1 cross-regression parameters that capture the lagged interactive influences between the dyad members. Specifically, the former represents the influence of parent *i*'s emotional valence at the previous time point on infant *i*'s emotional valence at the current time point whereas the latter represents the lagged influence of infant *i*'s emotional valence at time *t*-1 on parent *i*'s current emotional valence.

We allowed for random effects in the cross-regression but not the autoregressive parameters.[6] b_1 and c_1 are fixed effects parameters that capture the differences in interactive dynamics during the SF compared with the combined FF and RE episodes, whereas b_2 and c_2 represent the differences in interactive dynamics between the FF and RE episodes. The terms $u_{\phi_{parent->infant_{ik}}}$ and $u_{\phi_{infant->parent_{ik}}}$ capture dyad-specific deviations in cross-regression parameters that were not accounted for by the model, with variances, $\sigma^2_{u_{parent->infant}}$ and $\sigma^2_{u_{infant->parent}}$, respectively.

We hypothesized that the bidirectional interactive dynamics between parents and infants would be dominated by infant-to-parent influence. This was tested by sequentially constraining the intercept of each of the two cross-regression parameters to be zero and comparing the relative reduction in fit by means of likelihood ratio tests. That is, we first constrained the average infant-to-parent cross-regression parameter, c_0, to be zero and evaluated the corresponding change in -2 log-likelihood (-2*LL*) value. We then compared this particular change in -2*LL* to that obtained when b_0, the average parent-to-infant cross-regression parameter, was constrained to be zero.

Gender and ASD-sib status differences in interactive dynamics. To address the second modeling aim of the present article, namely, to assess potential between-dyad differences in interactive dynamics related to gender and ASD-sib status, we extended the model in Equation (1) to incorporate gender, ASD-sib status (denoted below as *Status*) and their interaction effects with other covariates as predictors of dyadic differences in the parent-to-infant and infant-to-parent cross-regression parameters as

$$\begin{aligned}
\phi_{parent->infant,ik} &= b_0 + b_1 SFvsFF/RE_{ik} + b_2 FTFvsRE_{ik} + b_3 Gender_i + b_4 Status_i + \\
& b_5 Gender_i * Status_i + b_6 Gender_i * SFvsFF/RE_{ik} + \\
& b_7 Status_i * SFvsFF/RE_{ik} + u_{\phi_{parent->infant_{ik}}} \\
\phi_{infant->parent,ik} &= c_0 + c_1 SFvsFF/RE_{ik} + c_2 FTFvsRE_{ik} + c_3 Gender_i + c_4 Status_i \\
& c_5 Gender_i * Status_i + c_6 Gender_i * SFvsFF/RE_{ik} + \\
& c_7 Status_i * SFvsFF/RE_{ik} + u_{\phi_{infant->parent_{ik}}},
\end{aligned} \tag{2}$$

where *Status* is a dummy-coded indicator with 0 = COMP-sib and 1 = ASD-sib, *Gender* indicates the gender of the infant (-1 = Male, 1 = Female) and the parameters $b_1 - b_7$ and $c_1 - c_7$ are fixed effects parameters used to explain dyad-specific variability in the parent-to-infant and infant-to-parent cross-regression parameters, respectively. These parameters revealed the impact of episode, gender, risk status and their interaction effects on the cross-regression parameters. A path diagram representation of this bivariate model is plotted in Figure 2.

To fit the bivariate models designed to address the first two modeling aims (see Equations 1 and 2), the approach described in MacCallum, Kim, Malarkey, and Kiecolt-Glaser (1997) was used in conjunction with the PROC MIXED procedure in SAS (Littell, Milliken, Stroup, & Wolfinger, 1996). Using this approach, the responses for parents and infants were stacked into a single vector and dummy indicators were used to combine the two processes into a single, univariate equation. In addition, the denominator degrees of freedom for assessing the statistical significance of the fixed effects parameters were adjusted using the Kenward-Rogers option (Littell et al., 1996) to control for the inflation in Type I error rate due to the presence of repeated measurements and the arbitrary gain in degrees of freedom resulted from stacking the responses from parents and infants into a single column of responses.

Within-dyad changes in infant-parent associations. The model in this section was developed to explore evidence for *nonstationarities* in *within-dyad dynamics*. The state-space formulation (Hamilton, 1994; Shumway & Stoffer, 2000) was used to structure our model. In particular, we sought to explore whether the concurrent associations between parents and infants changed dynamically within and between different FFSP episodes. Such time-varying changes in correlation patterns are one example of the ways in which individuals can manifest nonstationarities in the context of dyadic interaction. To capture potential changes in parent-infant synchrony, we added a stochastic regression component to a univariate AR model and examined whether and how the *concurrent linkages* between parents and infants changed over time within each dyad as

$$Infant_{ikt} = \begin{bmatrix} 1 & 0 & Parent_{ikt} \end{bmatrix} \begin{bmatrix} \alpha_{ikt} \\ \alpha_{ik,t-1} \\ B_{ikt} \end{bmatrix}, \tag{3a}$$

$$\begin{bmatrix} \alpha_{ikt} \\ \alpha_{ik,t-1} \\ B_{ikt} \end{bmatrix} = \begin{bmatrix} \phi_{1k} & \phi_{2k} & 0 \\ 1 & 0 & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} \alpha_{ik,t-1} \\ \alpha_{ik,t-2} \\ B_{ik,t-1} \end{bmatrix} + \begin{bmatrix} \zeta_{\alpha,ikt} \\ 0 \\ \zeta_{B,ikt} \end{bmatrix}, \tag{3b}$$

where $Infant_{ikt}$ represents infant *i*'s emotional rating in episode *k* at time *t*, $Parent_{ikt}$ is parent *i*'s emotional rating in episode *k* at time *t*, ϕ_{1k} and ϕ_{2k} are AR(1) and AR(2) parameters associated with episode k, α_{ikt} is a latent variable representing fluctuations in infant i's emotion that can be described using an AR(2) process and $\alpha_{ik,t-1}$ is its lag-1 counterpart needed to define the model as an AR(2) process. B_{ikt} is a time-varying regression parameter that captures the potentially time-varying association between the two dyad members. $\zeta_{\alpha,ikt}$ is the residual or process noise component associated with the AR(2) process and $\zeta_{B,ikt}$ is a residual or process noise component associated with B_{ikt}. The vector of residuals is constrained to conform to a covariance structure of

$$\begin{bmatrix} \zeta_{\alpha,ikt} \\ 0 \\ \zeta_{B,ikt} \end{bmatrix} \sim N\left(\begin{bmatrix} 0 \\ 0 \\ 0 \end{bmatrix}, \begin{bmatrix} \sigma^2_{\alpha_{0k}} + d_{1k} * Status_i & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & \sigma^2_{B_{0k}} + d_{2k} * Status_i \end{bmatrix} \right), \quad (4)$$

where $\sigma^2_{\alpha_{0k}}$ is the process noise variance of the AR process for COMP-sibs in episode k and d_{1k} captures the deviation in AR variance for ASD-sibs relative to the variance of COMP-sibs in episode k. By the same token, $\sigma^2_{B_{0k}}$ represents the process noise variance of the regression parameter for COMP-sibs over time in episode k and d_{2k} captures the deviation in regression variance for ASD-sibs relative to COMP-sibs in episode k. When the process noise variance of the regression parameter, $\sigma^2_{B_{0k}}$, is significantly different from zero, B_{ikt} is projected to vary over time following a random walk model—a relatively simple but well-known model that has been used in the past to represent, for instance, the path of a molecule as it travels in a liquid or gas, the price of a fluctuating stock, the path of a drunkard and the financial status of a gambler (Révész, 1990). The model in Equations 3-4 was fit separately to data from each episode.

In sum, the parent-infant regression component specified in Equations 3—4 differs from typical linear regression models seen in the literature in that the regression parameter is allowed to vary, rather than remaining invariant over time and individuals. Thus, it is typically termed the *stochastic regression model* (e.g., Shumway & Stoffer, 2000). In the special case in which $\sigma^2_{B_{0k}}$ is equal to zero, the time-varying regression parameter reduces to a time-invariant regression parameter and the regression component reduces to a standard linear regression model.

Equation (3a) is typically denoted as the measurement equation and it serves to link the manifest indicator, infant *i*'s valence rating in episode *k* at time *t* (i.e., $Infant_{ikt}$), to a vector of latent variables. Written in a one-step-ahead or difference equation form, Equation (3b) is the dynamic equation used to express the lagged relationships among the latent variables. A path diagram representation of the model is shown in Figure 3.

To summarize, the univariate AR model with stochastic regression expresses that an infant's emotional valence at time *t* can be decomposed into two main components: an AR(2) process denoted as α_{ikt}, and a time-varying regression model that links parents' emotion at each time point to infants' concurrent emotion through the time-varying regression parameter, B_{ikt}.[7] The AR(2) process, represented as an unobserved latent variable (see Figure 3), captures the ways in which a typical infant's emotion fluctuates around an equilibrium point. The equilibrium, rather than located at the absicca at $Infant_{it} = 0$ as in other earlier models, now varies over time contingent on the concurrent emotional valence of $Parent_{it}$. Furthermore, the extent to which the value of $Parent_{it}$ may shift the baseline of any particular infant's emotional valence is allowed to differ over time as well as over infants, as indicated by the time-varying regression parameter, B_{ikt}. To fit the model, B_{ikt} was parameterized as a latent variable whereas the regression path linking this "latent variable" to infant's manifest emotional valence is fixed at the value of the manifest parental emotional valence at the same time point (see Figure 3).

The dynamics associated with B_{ikt} were estimated over time using the Kalman smoother, specifically, the Fixed Interval Smoother (FIS; Dolan, & Molenaar, 1991, Otter, 1986). The FIS is a factor score estimation procedure that can be used to estimate values of the latent variables at each time point, including values of the (possibly) time-varying regression parameter, B_{ikt}, over time. In addition to using the FIS to obtain estimates of the latent variables, we used a maximum likelihood procedure known in the state-space modeling literature as the prediction error decomposition function (Schweppe,1965; Shumway & Stoffer, 2000) to estimate all the time-invariant parameters. These time-invariant parameters include the AR parameters, the residual variances and the deviation parameters, d_1 and d_2. All estimation procedures associated with the stochastic regression model were implemented using the SsfPack library in the OxMetrics program (Koopman, Shephard, & Doornik, 1999).

We expected ASD-sib dyads to show reduced levels of variability in their affective valence. The increased variability was expected to be reflected largely in the process noise variance of the AR(2) process. This was tested by evaluating the statistical significance of the term d_{1k}, which indicated whether there were statistically reliable deviations between the COMP-sibs and the ASD-sibs in their AR process noise variance. We also expected group level deficits in interactive coupling and responsivity to become accentuated during and after the perturbation in interaction caused by the SF. Thus, we expected the variances $\sigma^2_{B_{0k}}$ and $\sigma^2_{\alpha_{0k}}$ to be greater during the RE than the FF episode. We did not pose any directional hypotheses concerning whether and how the time variations in infant-parent concurrent associations differed between the ASD-sibs and COMP-sibs.

Results

General Lead-Lag Relationships between Parents and Infants

Results from fitting the bivariate AR model in Equation (1) indicated that all the infant and parent autoregressive parameters (including $\phi_{1,infant}$, $\phi_{1,parent}$, $\phi_{2,infant}$ and $\phi_{2,parent}$) were significantly different from zero at both lag 1 and lag 2. We had predicted bidirectional interactive dynamics between parents and infants that were dominated by infant-to-parent influence. As expected, we found significant bidirectional cross-regression relationships between infants and parents. That is, the average infant-to-parent and parent-to-infant cross-regression parameters across episodes, b_0 and c_0 (see Equation 1), were both significantly different from zero. In addition, constraining the average infant-to-parent cross-regression parameter, c_0, to be zero led to a substantial reduction in model fit (Δ-2*LL* = 51 on 1 *df*, $p < .001$). In contrast, when b_0, the average parent-to-infant cross-regression parameter, was constrained to be zero, the reduction in model fit was still statistically significant, but at a much reduced magnitude (Δ-2*LL* = 23 on 1 *df*, $p < .001$). This indicated that infants, as opposed to parents, played a leading role in determining the dynamics of the dyad.

The covariate *SFvsFF/RE* was found to have a significant main effect on both the infant-to-parent as well as parent-to-infant cross-regression parameters. During the FF and RE, the parent-to-infant and infant-to-parent cross-regression effects led to increased emotional fluctuations for both parents and infants. The significant effects of *SFvsFF/RE* on the cross-regression parameters, in contrast, indicated that the parent-to-infant and infant-to-parent coupling relations diminished almost completely during the SF condition. No significant difference in interactive dynamics was found between the FF and SF episodes. In addition, significant and marginally significant between-dyad differences still existed in the parent-to-infant and infant-to-parent coupling parameters, respectively, after the main effects of

SFvsFF/RE on the cross-regression parameters had been accounted for (i.e., $\sigma^2_{u_{parent->infant}}$ and $\sigma^2_{u_{infant->parent}}$ were significantly and marginally significantly different from zero). This suggests that even though overall parent-infant coupling diminished almost completely during the SF manipulation, some dyads continued to maintain some degree of coupling.

Between-Dyad Differences Related to Gender and Risk Status

Parameter estimates obtained from fitting the final version of Equation (2) in which only the statistically significant parameters and covariates were retained are summarized in Table 1. Relative to comparison sibs, we expected ASD-sib dyads to show generally lower levels of parent-to-infant as well as infant-to-parent coupling. Contrary to our hypothesis, ASD-sib status did not account for substantial between-dyad differences in the cross-regression parameters. In addition, no episode by *Status* interaction effect was found. This suggested that ASD-sib dyads did not show differential coupling patterns than COMP-sib dyads either in general or in specific FFSF episodes .

There was a significant *SFvsFF/RE* by infant gender interaction effect on the lag-1 infant→parent cross-regression parameter. Compared with the male infants, female infants continued to have slight positive lagged effect on their parents during the SF manipulation. In contrast, increased emotional fluctuations in male infants actually drove their parents to restrain their emotional valence further during the SF condition.

The collective dynamics of a dyad are determined jointly by both the auto- and cross-regression parameters. To aid interpretation of their combined effects, we generated hypothetical model-implied trajectories for parents and infants using the fixed effects parameter estimates from the final bivariate AR model (proposed under Modeling aim 2). We assumed that all of these hypothetical time series were corrupted by a common time series of process noise with a particularly notable perturbation at t = 1, which caused a pronounced drop in the participant's emotional valence at that time point. The trajectories (see Figures 4a-b) thus represent the predicted "recovery trajectories" of hypothetical parents or infants in different FFSF conditions toward their baseline or equilibrium.[8] In the current context, this baseline corresponded to the mean of the detrended residual scores (marked by the horizontal dotted line at the abscissa).

Examination of Figures 4a-b reveals that the regulatory trajectories of both dyad members were found to unfold at an especially rapid rate during the SF, particularly for parents. That is, as expected, the lack of active "input" or emotional perturbations from the parent resulted in both parents and infants exhibiting more controlled regulatory dynamics. These effects were conditioned by an interaction involving gender. Female infants continued to manifest attenuated lagged influence on parents during the SF. Increased emotional fluctuations in male infants, in contrast, actually expedited parents' regulation of their emotional valence during the SF even though the extent of lagged infant-to-parent influence was greater in these dyads during the FF and RE. It is worth noting that the emotional perturbations experienced by parents and infants were projected to show sinusoidal decay over time during the FF/RE but exponential decay during the SF. Even though the discrepancies between these two types of trajectories were too subtle to be noticeable visually from the plots in the present modeling example, the oscillatory nature of the recovery processes during the FF/RE reflects a unique feature of systems whose eigenvalues of the matrix of auto- and cross-regression parameters contain complex numbers; for details see chapter 1 of Hamilton, 1994; Wei, 1990). Such differences in affect regulatory style and may be indicative of important individual differences in other applications.

In sum, contrary to our initial hypotheses, no effects of risk status were found on lagged parent-child coupling. By contrast, there was a significant gender by *SFvsOTH* interaction such that parents of male infants, when compared to parents of female infants, exhibited more constrained emotional valence during the SF. Overall, despite the lack of support for some of our hypotheses, we confirmed that group-level gender differences between the FF/RE and the SF conditions in the dynamics of interaction could be extracted even after mean differences had been removed from the data.

Nonstationarities in Infant-Parent Associations

Parameter estimates obtained from fitting the state-space model expressed in Equations (3)-(4) to data from each of the three episodes are shown in Table 2. The group-based AR estimates obtained from analysis in this section were in the same range as the AR estimates obtained from fitting the mixed effects bivariate AR models.

We expected ASD-sib dyads to show reduced levels of variability in their emotional valence in the form of reduced AR(2) process noise. This hypothesis was supported (i.e., d_1 was significantly different from zero) by data from the SF and RE, but not the FF condition. Thus, ASD-sibs were less inclined to exhibit emotional perturbations in reacting to and recovering from the SF manipulation—differences that were not apparent during the FF.

We expected group level deficits in interactive coupling and responsivity to become accentuated during and after the SF. Thus, we expected the variances $\sigma^2_{B_{0k}}$ and $\sigma^2_{\alpha_{0k}}$ to be greater during the RE than the FF episode. We found support for this hypothesis. Both the process noise variance for the AR(2) process, $\sigma^2_{\alpha_{0k}}$, and the process noise variance for the regression parameter, $\sigma^2_{B_{0k}}$, showed an increase in magnitude from the FF to the RE. In particular, the process noise variance for the regression parameter (i.e., $\sigma^2_{B_0}$) was estimated to be significantly different from zero during the FF and RE, but not the SF. Estimates of the dyad-specific, time-varying regression parameter, B_{ikt} , derived using the FIS are plotted in Figures 5a-c. Consistent with the experimental manipulation, the regression parameters mainly clustered around zero during the SF episode. More importantly, whereas the regression estimates were observed to show within-episode fluctuations during both the FF and the RE, such infant-parent associations were much more volatile (i.e., showed greater, less systematic fluctuations) over the course of the RE episode than the FF episode. There were no significant risk status differences in the quantity of time-dependent variation in infant-parent associations within any of the three FFSF conditions (i.e., d_2 was not significantly different from zero in any of the three episodes).

Overall, we "decomposed" the variability in infants' emotional valence into two major components: a stochastic regression component that defined a time-varying baseline that reflected the time-varying nature of each dyad's infant-parent associations, and an AR component that captured the infants' fluctuations in emotional valence around their respective baseline as a group. Compared with COMP-sibs, we found that ASD sibs, on average, showed less emotional perturbations during both the SF and the RE. Compared to the FF episode, greater time variations in the concurrent synchrony (or asynchrony) between parents and infants were observed during the RE. This suggests that the SF manipulation increased time-based variation in the strength of interactive influence, an effect more subtle than mean level changes in infant affective valence.

Discussion

In the present article, we first addressed general lead-lag relationships between infants and parents during FFSF interaction. We then evaluated between-dyad differences, as well as within-dyad changes in parent-infant synchrony over time, using a series of mixed effects VAR(2) and stochastic regression models. Overall, the estimated AR parameters for the parents and infants were found to be similar in values across all models tested in the present study. The models indicated that the emotional valence of infants and parents was projected to return to an equilibrium point, as opposed to showing increasing deviations away from the equilibrium (i.e., showing amplified fluctuations), following a local perturbation.

Previous studies have suggested that ASD siblings show unique affective characteristics relative to comparison siblings during the FFSF protocol (Cassel et al., 2007; Yirmiya et al., 2006). Results across the two models tested in the present article suggest that ASD-sibs and COMP-sibs did not differ in their interactive regulation of emotion. That is, there were no group differences in the cross-regression parameters or process noise variance for the time-varying regression parameter, B_{it}, in the stochastic regression model. Rather, the stochastic regression model with AR(2) component indicated that the process noise variance of the AR process was significantly higher among COMP-sibs than ASD-sibs during the SF and RE episodes. That is, COMP-sibs tended to show greater emotional fluctuations during the SF that persisted into the RE episode. This finding is consistent with previous evidence suggesting that ASD-sibs tend to show more neutral affect relative to other COMP-sibs during the FFSF procedure (e.g., Yirmiya et al., 2006). Here, we provided support for this conjecture from a dynamic regulatory perspective. This suggests subtle flattening in the auto-regulation of ASD-sibs that was independent of their mean or individual level of affective valence.

Beebe et al. (2007) used a set of univariate mixed effects AR(1) models to demonstrate the presence of both parent-to-infant and infant-to-parent influence in the interactions of four-month-olds and their mothers. Here, we incorporated both AR(1) and AR(2) parameters to capture possible damped oscillatory dynamics in the participants' emotion regulation trajectories (Hamilton, 1994; Harvey, 1993). The modeling work undertaken in the current study extended the approach adopted by Beebe et al.'s (2007) by allowing for simultaneous examination of infant-to-parent and parent-to-infant lagged influences (or interactive contingencies) within one bivariate random effects AR model. Consistent with findings that infant-parent attachment emerges through ongoing, reciprocal but infant-dominated exchanges between infants and parents (Feldman, 2006; Jaffe et al., 2001; Moore et al., 1997; Stern, 1985), we found a significant bidirectional coupling between the affective dynamics of parents and infants that was relatively dominated by infant-to-parent influences. Phrased in the context of a three-legged race, the bidirectional ties between parent and infant in a dyad helped deter both parties from settling into a stagnant state too quickly, with the infant serving as the "leading member" of the race.

The relative dominance of infant-to-parent influences was validated by means of likelihood ratio tests. Such tests provide a more objective, quantifiable basis for testing the lead-lag relationships between infants and parents compared to exploratory indices such as time-lagged cross-correlations (Yirmiya et al., 2006). Contrary to results reported by Yirmiya at al. based on individual classification of dyads, our group-based approach indicated no evidence for deficits in parental responsivity to changes in infant emotional engagement among ASD-sib dyads.

With appropriate parameter constraints, the AR(2) model can be regarded as a discrete-time counterpart of the damped oscillator model used by Chow et al. (2005) to test the notion of emotion as a thermostat (see Harvey, 1993; Harvey & Souza, 1987). The AR model is a well-known model in the time series literature and it includes a different set of parameters indicative of the nature and dynamics of the process of interest (Hamilton, 1994; Shumway & Stoffer, 2000; Wei, 1990). The damping and frequency parameters inherent in the model in Chow et al. (2005) can only be obtained from the AR model through added parameterization constraints (see Harvey, 1993; Hamilton, 1994), but the AR formulation has some other critical advantages. For one, the AR model is generally more familiar to the broader social sciences community compared with the damped thermostat model in differential equation form; it is also relatively easy to implement using standard software packages such as SAS and SPSS. For another, compared to a strictly cyclic model that is characterized by one fixed frequency, the AR(2) is flexible enough to capture less structured, quasi-cyclic dynamics (Wei, 1990). This is an important characteristic of parent-infant interaction data because nonperiodic cycles, as opposed to periodic cycles, are much more prevalent in the behaviors of parents and young infants (Cohn & Tronick, 1988).

One cautionary note pertaining to the interpretation of the auto- and cross-regression parameters is in order. Higher self-contingencies (i.e., higher AR(1) coefficients) in mother's behaviors during face-to-face play with infants have conventionally been regarded as reflecting greater predictability and a more adaptive interaction style (e.g., Beebe et al., 2007). Whereas this interpretation may be meaningful in the range of low to moderate AR(1) values (specifically, values that are positive but substantially less than 1.0 such as the .5-.7 range in Beebe et al.'s study), the same interpretation may not apply in cases involving AR(1) values that are close to or above 1.0, which were observed in the present study). Within this elevated range , relatively high "self-contingencies" may lead to increasing emotional fluctuations and consequently, a highly unstable system that shows increasing fluctuations in affective dynamics. The inclusion of cross-regression parameters—interactive contingencies—can further alter the dynamics of the system. Thus, the proposition put forth by Jaffe et al. (2001), that midrange interactive contingencies between mothers and infants lead to more secure attachment than low or high contingencies, may be particularly pertinent in the interpretation of AR-based models. From a modeling standpoint, mid-range interactive contingencies may help strengthen the regularity in both parties' affect without pushing a dyad into an unstable state. Regardless, the substantive meanings of the AR parameters have to be considered carefully in regard to the dynamics generated by the modeling parameters as a whole, and the context within which the notion of "baseline" is defined.

Research on infants' interactive dynamics in the past few decades has been dominated largely by a "static" notion of development. Yet there may be a growing consensus that change, as opposed to stability, captures a fundamental facet of children's socioemotional functioning and development (Fogel & Thelen, 1987; Moore et al., 1997). For instance, De Weerth and van Geert (2002) reported that emotional behaviors in mother-infant dyads showed substantial variability during the first year of life, both between dyads and between behaviors. Using the current modeling approach, we found that parent-infant synchrony changed substantially both within relatively brief interaction episode as well as between different FFSF episodes. In particular, the SF procedure did not eliminate individual differences in subtle interactive dynamics between parents and infants, but did change subsequent dyadic interactions (see Figures 5a-c). During the FF, the parent-infant associations (i.e., the time-varying regression weights) were observed to unfold more gradually following relatively smooth trajectories. In contrast, the parent-infant associations during the RE were characterized by more divergent differences across dyads and relatively unstructured fluctuations that unfolded at a more rapid rate. The rich dynamics embedded in such within-dyad fluctuations can be easily bypassed, however, if time-based changes in interactive dynamics are examined.

The current procedures used to identify intra-dyad variability in parent-infant coupling can be readily utilized to study other dynamic phenomena in psychology. We used a simple random walk process to represent changes in the parent-infant association parameter within dyads because of its flexibility in approximating very diverse patterns of change with very little modeling constraints. More theoretically driven models, can be used to test specific notions of how these associations vary over time. Approaches such as regime switching models (Kim & Nelson, 1999), change point detection models (Carlin, Gelfand & Smith, 1992) and nonlinear state-space models with time-varying parameters (Chow, Ferrer & Nesselroade, 2007; Molenaar & Newell, 2003) are all examples of other alternatives for representing complex changes in dyadic linkages.

Given that our modeling results were based on data provided by non-expert raters, there may be delays and imprecision in ratings. However, because the ratings used for model fitting were aggregated and standardized across multiple raters, these ratings served as a helpful proxy for validating the directionality of parent-infant coupling. For instance, we still found support for the much corroborated view of mutual infant-parent reciprocity (bidirectionality) despite the possible existence of rating delays. Automated measurement techniques with high time precision may be useful in further clarifying the nature and directionality of infant-parent coupling (Messinger, Mahoor et al., 2008; Messinger, Cassel et al., 2008). In fact, findings of time-varying interactive influence in the present study are a formalization of observations of apparent non-stationarities made with reference to a pair of case studies of dyadic interaction that relied on computer vision measurements of facial expression (Messinger, Mahoor, Chow, & Cohn, 2009).

Admittedly, the sample size in the current study (in terms of the number of dyads) was small relative to the complexity of some of the models considered herein, particularly the mixed effects models. Standard error estimates turned out to be reasonable, although other more subtle between-dyad differences could probably be identified with greater accuracy if data were available from more dyads. Viewed from a different angle, the availability of intensive repeated measurements data does help provide additional information concerning patterns of intraindividual changes, and such data, as we have shown here, help open up new possibilities for exploring more subtle changes and potential nonstationaries within dyads.

Conclusion

Intra-individual changes and inter-individual differences have been described metaphorically by Nesselroade (1991) as the warp and woof of the developmental fabric, respectively. The warp (intra-dyad dynamics) and woof (inter-dyad differences) of interactions are equally critical to our understanding of what distinguishes a dyad from two individuals who act in isolation. The overarching goal in the present article was to present possible ways of conceiving and describing dyads as intertwined dynamic systems. The different dynamic models used in this study are but one of the many ways of representing patterns of dyadic interactions. We hope that the potential promises of these methods can help researchers envision a more enriched notion of the processes that govern dyadic interactions, and possibly inspiring them to design studies that not only capture the constancy, but also the variability in dyadic interaction.

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Footnotes

[1] Statistically, strict stationarity refers to the invariance of all distributional properties of a system over time. A weaker form of nonstationarity is covariance stationaritiy, which is used to describe systems that have finite second moments and show invariance in their mean and covariance functions over time (see Hamilton, 1994; Shumway & Stoffer, 2000).

[2]We replicated all analyses using data from all but the two infant-father dyads. Results were virtually identical to those obtained using the full sample.

[3] The CMS is available for download at http://measurement.psy.miami.edu/cms.phtml.

[4]Raters rated the videos without access to audio. This is because the parent and infant videos contained the same audio track and we wanted to obtain valence ratings for each infant or parent independent of the influences imposed by the presence of the other dyadic member.

[5]The use of a unidimensional valence rating scale was reasonable within our modeling context given the apparently bivalent nature of infant affective valence (Messinger, 2002) and the need to include both infant and parental affective valence in our bivariate model.

[6]We acknowledge that failure to include random effects for the autoregressive parameters can potentially inflate the random effects estimates attributed to the cross-regression parameters. However, a model that included the four random effects components (random effects for the two autoregressive parameters and two cross-regression parameters) were computationally intensive and did not converge. Ultimately, the model in Equations 1—2 was chosen to strike a balance between modeling parsimony and theoretical relevance.

[7]Infant emotional valence was used as the dependent variable in this model but this choice is, to some extent, arbitrary. Rather than working directly with the bivariate AR model in Equations 1—2, we chose to fit a univariate AR model in the form of Equations 3—4 because specifying

the cross-regression parameters in the bivariate AR models (see Equations 1—2) to be time-varying introduces nonlinearity and added modeling complexities in the model that cannot be handled by standard linear estimation techniques. In the present context, we made infants the “dependent variable” of interest because parents, by virtue of their role in the SF procedure, can be conceived as an external source of perturbations to the infants. The ways in which the infants reacted to these external inputs (i.e., parents’ changes in responsiveness) constitute a central question of interest. Making parent, as opposed to infant, as the dependent variable does not provide any unique information compared to the model expressed in Equations 3—4 and was thus not considered separately.

[8]Of course, the error variance estimates associated with the different empirical scenarios were all different so a direct comparison of the recovery trajectories by varying the auto- and cross-regression parameters alone is arbitrary. Nevertheless, the predicted trajectories provide some indications on the ways in which parents and infants “self-regulate” their emotion toward their respective equilibrium points when all other modeling components are held equal.

Table 1.

Parameter Estimates Obtained from Fitting the Final Bivariate VAR(2) Models.

Parameters	Estimates (SE)	Parameters	Estimates (SE)
Infant AR(1) parameter ($\phi_{1,infant}$)	1.33 (.01)	Gender on I → P (c_3)	.001 (.005)*
Infant AR(2) parameter ($\phi_{2,infant}$)	-.40 (.01)	SFvsFF/RE on I → P (c_1)	-.04 (.01)
Parent AR(1) parameter ($\phi_{1,parent}$)	1.03 (.01)	SFvsFF/RE x Gender on I → P (c_6)	.02 (.006)
Parent AR(2) parameter ($\phi_{2,parent}$)	-.24 (.01)	Between-dyad variance in P → I ($\sigma^2_{u_{parent->infant}}$)	.0004 (.0002)
Baseline P → I (b_0)	.03 (.01)	Between-dyad variance in I → P ($\sigma^2_{u_{infant->parent}}$)	.0003 (.0002)**
SFvsFF/RE on P → I (b_1)	-.02 (.005)	Error variance for parent ($\sigma^2_{e_{parent}}$)	.25 (.003)
Baseline I → P (c_0)	.05 (.01)	Error variance for infant ($\sigma^2_{e_{infant}}$)	.19 (.002)

Note: P → I = parent-to-infant cross-regression parameter; I → P = infant-to-parent cross-regression parameter. All parameter estimates except for c_3 and $\sigma^2_{u_{infant->parent}}$ were statistically different from zero at the .05 level.

* p = .79. The parameter c_3 was included in the model to aid interpretation of the *SFvsFF/RE* x *Gender* interaction effect on the infant-to-parent cross-regression parameter.

** p = .06.

Table 2.

Time-Invariant Parameter Estimates Obtained from Fitting the AR Model with Stochastic Regression Component to Data from Each of the Three Episodes.

Parameters	Estimates (SE) for FF	Estimates (SE) for SF	Estimates (SE) for RE
Group-based AR(1) parameter (ϕ_1)	1.24 (.01)*	1.02 (.02)*	1.25 (.01)*
Group-based AR(2) parameter (ϕ_2)	-.40 (.01)*	-.27 (.02)*	-.42 (.01)*
Group-based variance for AR(1) component ($\sigma^2_{\alpha_0}$)	.39 (.01)*	.59 (.01)*	.45 (.01)*
Group-based variance for time-varying regression coefficient ($\sigma^2_{B_0}$)	.012 (.005)*	.01 (.02)	.04 (.01)*
AR variance difference (ASD-sibs - COMP-sibs; d_1)	.003 (.006)	-.05(.02)*	-.08 (.01)*
Regression variance difference (ASD-sibs - COMP-sibs; d_2)	.00 (.00)	-.00 (.00)	.00 (.00)

* $p < .05$

Figure Captions

Figure 1. Screenshot of the Continuous Measurement System (CMS).

Figure 2. Path diagram of the bivariate AR(2) model. The dark filled circles attached to the lag-1 cross-regression paths, $\phi_{infant->parent,i}$ and $\phi_{parent->infant,i}$ indicate that individual differences are included in the P→I and I→P cross-regression parameters. The index for episode (*k*) is omitted from the path diagram to simplify the notations. $Infant_{it}$ = manifest measurement of infant (in dyad) *i*'s emotional valence at time *t*; $Parent_{it}$ = manifest measurement of parent (in dyad) *i*'s emotional valence at time t $e_{infant,it}$ = measurement error for infant ; $e_{parent,it}$ = measurement error for parent; $\sigma^2_{e,infant}$ = measurement error variance for infant; $\sigma^2_{e,parent}$ = measurement error variance for parent; $\phi_{1,infant}, \phi_{1,parent}, \phi_{2,infant}, \phi_{2,parent}$ = AR(1) parameter for infant, AR(1) parameter for parent, AR(2) parameter for infant and AR(2) parameter for parent; $\phi_{infant->parent}$ = cross-regression from infant's emotion at time *t*-1 to parent's emotion at time *t*; $\phi_{parent->infant}$ = cross-regression from parent's emotion at time *t*-1 to infant's emotion at time *t*.

Figure 3. Path diagram of the stochastic regression model with AR(2) component used to represent time-varying concurrent synchrony between parents and infants. The index for episode (*k*) is omitted from the path diagram to simplify the notations. $Infant_{it}$ = manifest measurement of infant (in dyad) *i*'s emotional valence at time *t*; $Parent_{it}$ = manifest measurement of parent (in dyad) *i*'s emotional valence at time *t*; $Status_i$ = ASD status for infant *i* (0 for COMP-sibs, 1 for ASD-sibs); α_{it} = AR component; ϕ_1 =AR(1) parameter; ϕ_2 =AR(2) parameter; B_{it} = regression parameter at time *t*; $\sigma^2_{\alpha_0}$ = variance for AR component; $\sigma^2_{B_0}$ = variance for time-varying regression parameter; d_1 = deviation in AR variance associated with ASD-sibs compared with

COMP-sibs; d_2 = deviation in variance for the regression parameter associated with ASD-sibs compared with COMP-sibs.

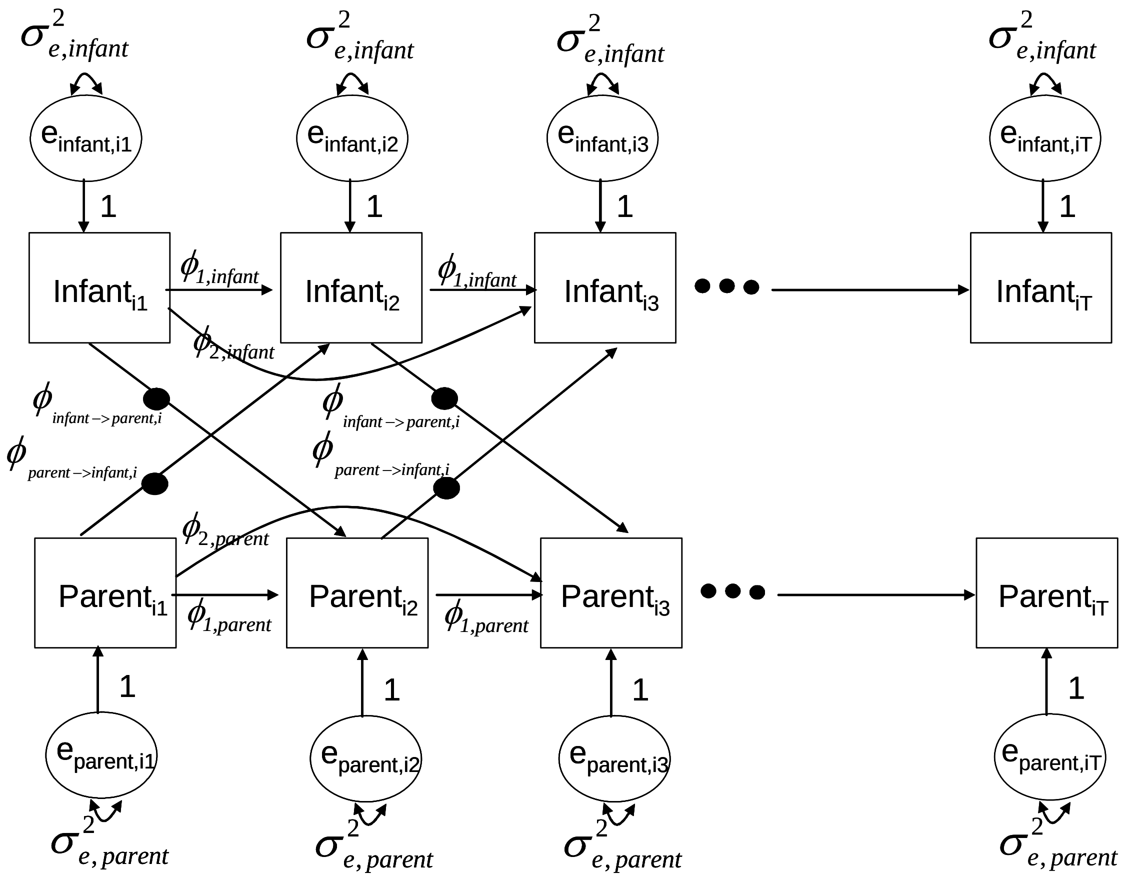
Figure 4. Predicted trajectories of parents and infants across different FFSF conditions. One time series of residual errors, e_t , is used in all simulations to generate the same magnitudes of perturbations in all conditions. The horizontal dotted lines in (a) and (b) represent the baseline affective level toward which each participant's recovery trajectory converges. (a) Predicted trajectories of parents of male vs. female infants in the SF vs. FF/RE condition. *M, FF/RE* = parent of male infant during the FF/RE; *F, FF/RE* = parent of female infant during the FF/RE; *M, SF* = parent of male infant during the SF; *F, SF* = parent of female infant during the SF; *comparison* = comparison trajectory generated by setting *Gender* and *SFvsFF/RE* to 0, the average of the respective contrast codes for *Gender* and *SFvsFF/RE*. (b) Predicted trajectories of infants in the SF vs. FF/RE condition. FF/RE = infant during the FF/RE, SF = infant during the SF. *comparison* = comparison trajectory generated by setting *SFvsFF/RE* to 0, the average of the contrast code of *SFvsFF/RE*.

Figure 5. Estimated regression weights for each dyad based on parameter estimates from the final AR with stochastic regression model. The regression weights were estimated by means of the FIS for (a) the FF episode, (b) the SF episode and (c) the RE episode.

Figure 1

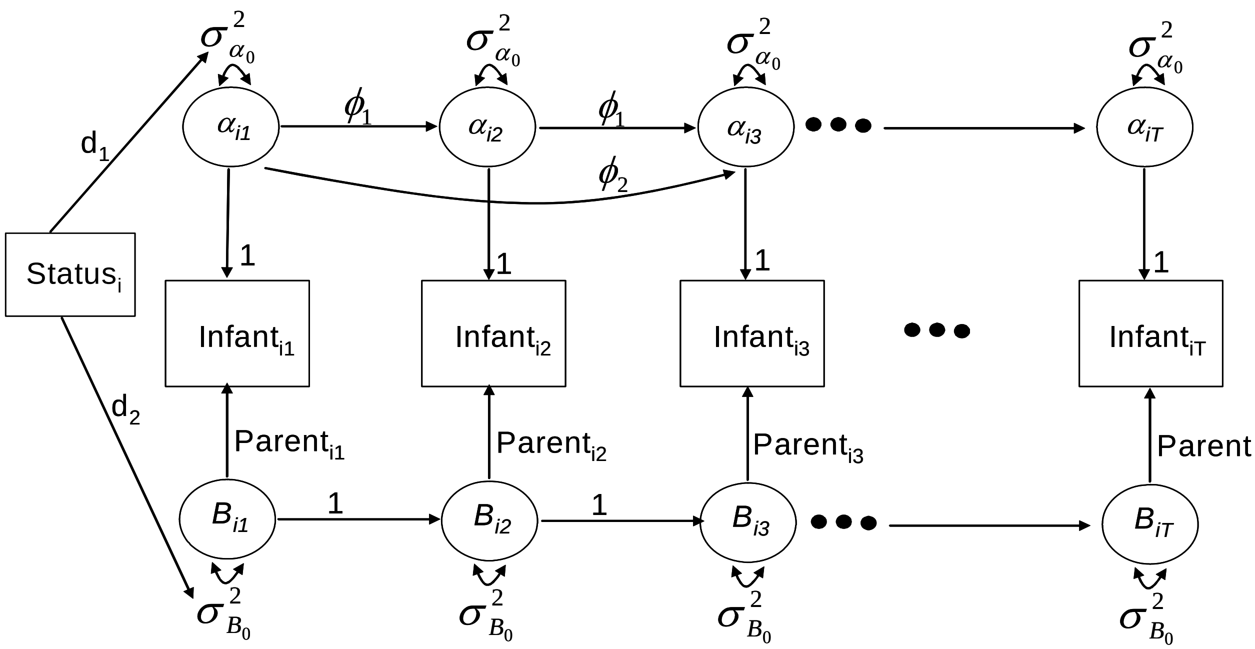

Continuous Measurement System 3.0
File
View
Tools
Data
Help
Emotional Valence
Positive
Negative
Playback started.
Session ID: 10013

Figure 2



$\sigma^2_{e,infant}$
$e_{infant,i1}$
$e_{infant,i2}$
$e_{infant,i3}$
$e_{infant,iT}$
1
$Infant_{i1}$
$Infant_{i2}$
$Infant_{i3}$
$Infant_{iT}$
$\phi_{1,infant}$
$\phi_{2,infant}$
$\phi_{infant->parent,i}$
$\phi_{parent->infant,i}$
$\phi_{2,parent}$
$\phi_{1,parent}$
$Parent_{i1}$
$Parent_{i2}$
$Parent_{i3}$
$Parent_{iT}$
$e_{parent,i1}$
$e_{parent,i2}$
$e_{parent,i3}$
$e_{parent,iT}$
$\sigma^2_{e,parent}$

Figure 3



$\sigma^2_{\alpha_0}$
$\sigma^2_{\alpha_0}$
$\sigma^2_{\alpha_0}$
$\sigma^2_{\alpha_0}$
d_1
α_{i1}
ϕ_1
α_{i2}
ϕ_1
α_{i3}
α_{iT}
ϕ_2
1
1
1
1
$Status_i$
$Infant_{i1}$
$Infant_{i2}$
$Infant_{i3}$
$Infant_{iT}$
d_2
$Parent_{i1}$
$Parent_{i2}$
$Parent_{i3}$
Parent
B_{i1}
1
B_{i2}
1
B_{i3}
B_{iT}
$\sigma^2_{B_0}$
$\sigma^2_{B_0}$
$\sigma^2_{B_0}$
$\sigma^2_{B_0}$

Figure 4

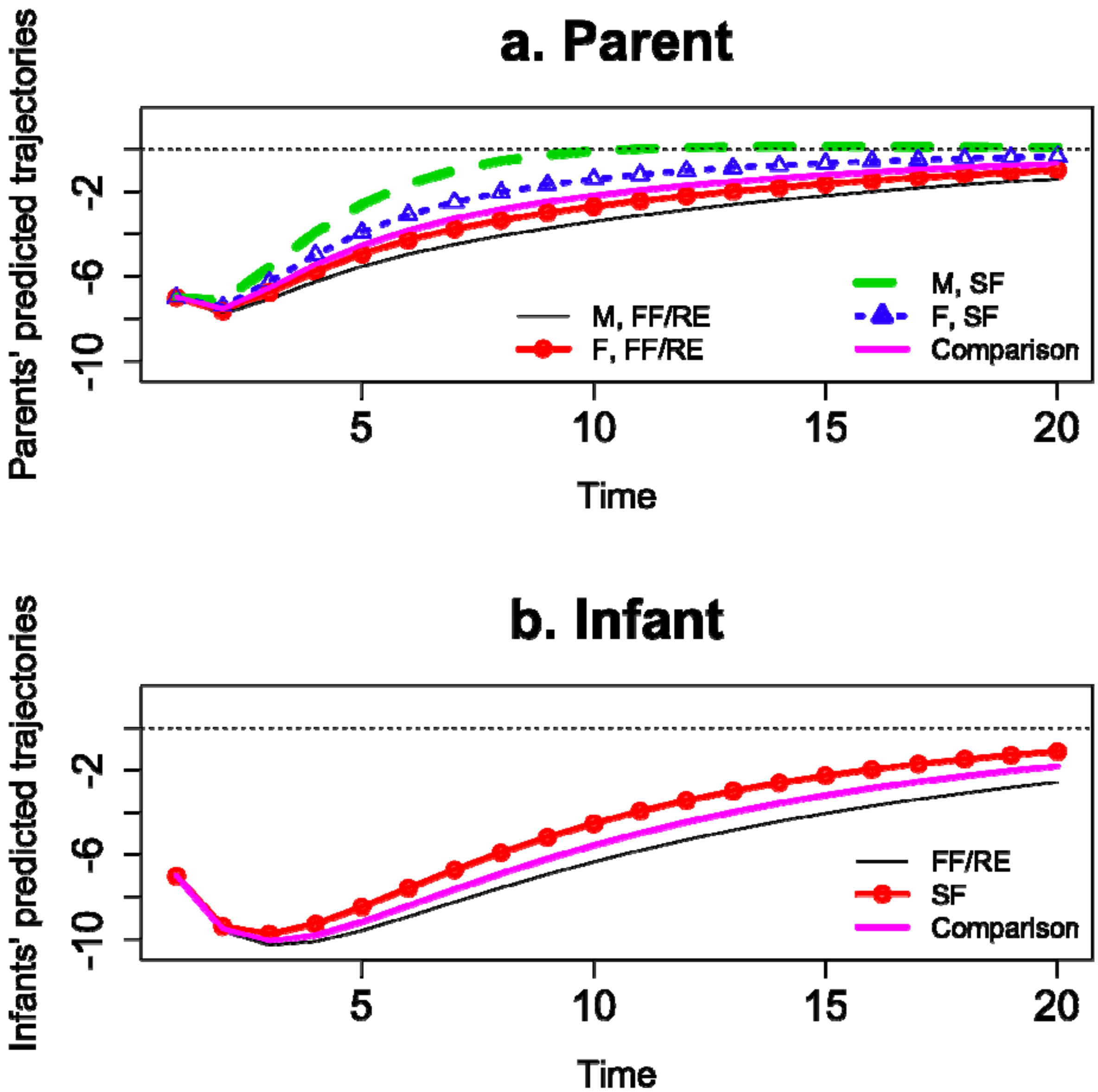
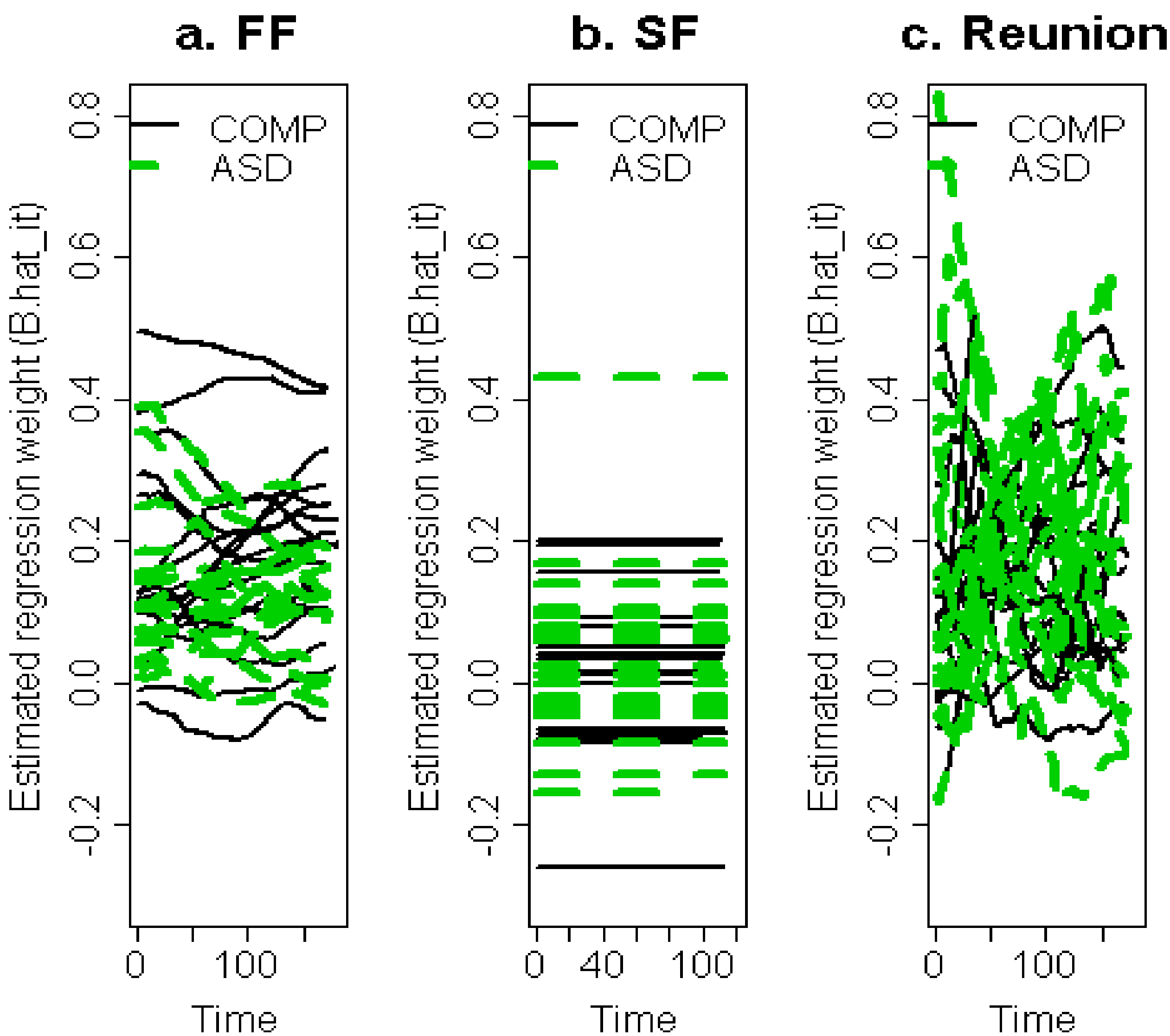

a. Parent
Parents' predicted trajectories
-2
-6
-10
5
10
15
20
Time
M, FF/RE
F, FF/RE
M, SF
F, SF
Comparison
b. Infant
Infants' predicted trajectories
-2
-6
-10
5
10
15
20
Time
FF/RE
SF
Comparison

Figure 5


a. FF
b. SF
c. Reunion
COMP
ASD
Estimated regression weight (B.hat_it)
Time
0.8
0.6
0.4
0.2
0.0
-0.2
0
40
100