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Mathematical Models for Coordinated Interpersonal Timing in Mother–Infant Interactions in the First Year of Life

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Two mathematical models of social contingency are examined in terms of their development over the first year of life. The interactions of 53 mothers and their infants were recorded at 6 weeks, 4 months, and 12 months. The infants' gazes at 6 weeks, the mothers' vocal behavior at 6 weeks, and the vocal behavior of the mother and infant at 4 and 12 months were automatically coded in terms of four states. The conditional dependence model and the response effects model were computed for each interaction at each age, and the coefficients of the models were examined as a function of age. The relative success of the models as estimates of moment-to-moment contingency as well as their variations with age are discussed.

Infants appear to be exquisitely prepared for sensitive interpersonal interactions from birth. For example, numerous, carefully designed and executed studies have documented the infants' extraordinary abilities for intermodal/cross-modal perception and representation and the relationship of this ability to caregiver behavior (e.g., Bushnell, Weinberger, & Sasserville, 1989; Meltzoff, Kuhl, & Moore, 1991; Rose & Ruff, 1987). Infants behave in ways that express a high degree of temporal organization, and, again, differences in the degree of this organization also relate to caregiver behavior

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(e.g., Zeskind & Marshall, 1991). This temporal organization also reflects the integrity of the infant's nervous system (Bahrick, 1983). Other studies have demonstrated that young infants are "active listeners" who show discrimination of and responses to acoustic cues as early as the interuterine environment (e.g., DeCasper & Spence, 1991). Most relevant to the issue are studies of the contingencies within mother–infant interactions.

Several studies found evidence for a high degree of contingency in the behavioral displays of mother–infant interactions (e.g., Thomas & Malone, 1979; Thomas & Martin, 1976), but the findings indicated that the contingency may have been based upon the mothers' molding their behavior to respond to the infants'. Lester, Hoffman, and Brazelton (1985) used spectral and cross-spectral techniques to "estimate coherence of interactional rhythms" in 40 term and preterm mother–infant interactions. Their findings indicated the presence of periodicities and also interactional synchrony. Cohn and Tronick (1988) also found evidence for interactional influence, but did not find evidence for periodic cycles except in 3-month old infants. Cohn and Tronick found evidence that the infants not only influenced the mothers' behavior, but were also influenced by it. Feldstein et al. (1993) reported findings of coordinated interpersonal timing of both mother and infant behavior during the first year. It should be noted that these studies have tended to examine different behavioral systems and to use different methods for estimating contingency. Nevertheless, they seem to concur in the conclusion of the presence of temporal coordination in mother–infant interactions. However, they disagree regarding the nature of the coordination.

It has been argued that to the extent that we are able to quantify phenomena we are able to understand them (e.g. Wickens, 1982). With that in mind, the purpose of the present report is to apply two different mathematical models for assessing coordinated interpersonal timing in mother–infant interactions. The first model, here referred to as the conditional dependence model, is the procedure proposed for this purpose by Jaffe, Stern, and Peery (1973; originally proposed by Jaffe, Feldstein, & Cassotta, 1967, for the study of adult dialogues). It posits that the participants make independent decisions based only on the state of the interaction at the moment. The second model, here referred to as the response effect model, proposed by Thomas and Malone (1979), is an elaboration of the conditional dependence model that partitions individual response to account for individual *bias*, *own* and *other sensitivities*, and *interaction*.

The advantage of the response effect model is that it elaborates the conditional dependence model in terms of self- and other-influences. However, the elaboration has some problems of its own. First of all, Thomas and Malone (1979) implied that an advantage of the response effect model is that it separates partner effects—in this case, that it separates degree to which the infant is contingent from the degree to which the mother is contingent. However, as can be seen from the definitions of the effects in the model later in this paper, it is clear that each effect is calculated on the basis of both partners' behaviors. A second limitation of the response effects model is the confusion of the typical meaning of the terms used to describe the effects (*bias*, *own sensitivity*, etc.) with what they appear to mean on the basis of their estimation. For example, the use of the term *interaction* for the fourth effect implies that it is interpersonal, or that it is analogous to Cohn and Tronick's (1988) cross-correlation. Yet the effect of *interaction* is computed on the basis of the proportion of time that the partner in question talks when exactly one partner is talking minus the proportions when neither or both are talking. Similarly confusing, *own sensitivity*, which seems to imply autocorrelation, consistency, and stability, is calculated as the proportion of time the target partner talks while holding the floor. In both of these cases, it seems that the terms used by Thomas and Malone confound the behavior in question with their possible function in a manner that is difficult to justify on a purely objective basis. However, although these terms themselves may be a bit misleading, the functions they characterize do represent useful measures.

METHOD

Participants

A subsample of 53 dyads was selected for reanalysis from the same project that supplied the participants for the study reported by Feldstein et al. (1993). The selection criteria for the "New York Site" are thoroughly described in the latter report:

> The inclusion criteria were: (a) mothers had to be at least 18 years old; (b) both mother and infant were in a stable nuclear family situation; (c) mother's primary language was English; (d) mother had a telephone in her home; (e) mother exhibited no gross psychopathology during initial contact; (f) mother did not have a positive prenatal urine drug screen; (g) mothers did not have preeclampsia or significant medical complications; (h) Caesarean section was acceptable if there were no evidence of fetal distress; (i) the infant was a singleton birth; (j) 1-min Apgar below 7 was acceptable only if 5-min Apgar was equal to or greater than 7; (k) birthweight was not less than 2,500 gms; (l) the infant was not more than 3 weeks preterm or 2 weeks postterm; (m) infants did not have a positive urine toxicology screen; (n) infants with abnormal blood gases were acceptable if they met all the other inclusion criteria; (o) approval for suitability was given by the attending obstetrician; and (p)

infant was discharged from hospital at same time as mother. (Feldstein et al., 1993, p. 458).

For this study, only the dyads who participated at all three ages, that is, 6 weeks, 4 months, and 12 months of age, were included in the analyses.

Instruments

The instruments and data-collection procedures were also detailed in the Feldstein et al. (1993) report. The behaviors examined were determined by the four vocal/gaze states (defined below) in the mother–infant dyad. At 4 and 12 months old, the vocal sounds and silences of the mother and the infant were examined. However, at 6 weeks, while the vocal sounds and silences of the mother were also measured, the visual attention behavior of the infant was assessed. The latter was justified on the basis of the low production of noncry vocalizations at 6 weeks (see, for example, Beckwith, Sigman, Cohen, & Parmelee, 1977; Stark, 1981), on the vast literature on cross-modal integration (e.g., Meltzoff et al., 1991), and on the compelling evidence that the infant uses gaze to operate social control (e.g., Stern, 1971).

Procedure

The mothers brought the infants to the interpersonal communications laboratory at the New York State Psychiatric Institute when the infants were 6 weeks, 4 months, and 12 months postpartum. The mothers were given transportation costs to the laboratory. Face-to-face play interactions were audio- and video-recorded at each age. If an infant became fussy to the point of crying, and if the crying persisted for longer than 10 s, the interaction was interrupted. The period of crying was deleted from the tape. Taping was resumed when the infant entered an alert inactive state (Wolff, 1966). Taping took place in a soundproofed room and contact microphones were used.

Behavioral Coding Procedure

The vocal behavior of each interaction was coded by direct input of two audio signals, one each for the adult and infant, into the Automated Vocal Transaction Analyzer originally described by Jaffe and Feldstein (1970). For the 6-week interactions, the infant's visual behavior was input to the system via a microswitch that was depressed by a human coder each time the infant looked directly at the mother's eye–face region, while the mother's vocal behavior was simultaneously input to the second channel. After numerous practice sessions, the interrater and intrarater reliability of infant gaze by two graduate students was established at $r = .90$ (on the basis of average durations of gaze on and gaze off per minute over the course of a given interaction) before the coded interactions were accepted as "true data." Reliabilities were monitored on an on-going basis for randomly selected interactions. Raters were able to maintain reliability that ranged between $r = .84$ and $r = .93$ over the coding of all of the interactions.

Data Analytic Strategies

Conditional Dependence Model. The conditional dependence model (originally called the independent decision model) factors Markovian probabilities into two independent values determined by the two participants in the interaction. The Markovian analysis describes transition probabilities from state to state in the system. The states are identified as follows:

0 = neither partner involved
1 = mother vocalizes, infant uninvolved
2 = infant involved, mother silent
3 = both involved

where *involved*, for these purposes, refers to vocalizing except in the case of the 6-week-old infants, where it refers to visual attention. A transition probability has the form p_{ij}, the probability that the system is in state j at time t, given that it is in state i, at time $t - 1$. The time intervals are 250 ms. The conditional dependence model factors each p_{ij} as the product of two quantities, each determined by one member of the dyad. The transition probability p_{ij} is factored as follows:

$$p_{i0} = (1 - q_i)(1 - r_i)$$

$$p_{i1} = q_i(1 - r_i)$$

$$p_{i2} = (1 - q_i)r_i$$

$$p_{i3} = q_i r_i$$

where

q_i = P(mother vocalizes at time t, given the system is at state i at time $t - 1$)
r_i = P(infant involved at time t, given the system is at state i at time $t - 1$)

where *involved* is defined as above. As can be seen, this model factors transition probabilities into quantities determined by the individuals.

The values of q_i and r_i were estimated for each mother–infant interaction, at each age level, and a fit of the model was measured using the Neyman-Pearson statistic as described by Jaffe and Feldstein (1970).

The Response Effect Model. The model called here the response effect model, introduced by Thomas and Malone (1979), combines each individual's response variables from the conditional dependence model into four measures described as *bias*, *own* and *other sensitivity*, and the *interaction*. This model separates each individual's behaviors into four contrasts. Thomas and Malone defined the mother's response effects as follows:

Bias:	B_m	$= .25(q_0 + q_1 + q_2 + q_3)$
Own sensitivity:	S_m	$= .25(-q_0 + q_1 - q_2 + q_3)$
Other sensitivity:	I_m	$= .25(-q_0 - q_1 + q_2 + q_3)$
Interaction:	SI_m	$= .25(-q_0 + q_1 + q_2 - q_3)$

Bias is the average of the mother's four response probabilities. Own sensitivity is a measure of how likely the mother is to continue her behavior. (If it is as large as it can be, .5, it indicates that the mother only speaks when she spoke before. If it is as small as it can be, it indicates that the mother only speaks when she was previously silent.) Other sensitivity measures the likelihood that the mother's behavior is affected by the infant. (Its maximal value occurs in the situation where the mother speaks only when the infant was involved in the previous moment. The minimal value has the mother only speaking when the infant was uninvolved in the previous instant.) Interaction is a measure of the mother's response to similarity or difference in dyadic behaviors. (It gets its maximal value when the mother and infant were behaving differently in the previous moment, i.e., the mother speaks when, at the previous moment, the infant was involved and the mother silent or the mother was speaking and the infant was uninvolved. It gets its minimal value when mother only speaks when she and the infant were behaving similarly in the previous instant.) The .25 factor in each equation provides normalization.

The corresponding values for the infant (B_0, S_0, I_0, SI_0) can be obtained by replacing q_0 with r_0, q_1 with r_2, q_2 with r_1 and q_3 with r_3 in the right-hand side of the corresponding expressions above. Each of the eight response effects was estimated for each mother–infant interaction at each of the three ages.

RESULTS

Conditional Dependence Model

The Neyman-Pearson statistic (NPS) was computed for each dyad at each age. The percentage of coefficients that was significant at 6 weeks was

25%, at four months was 90%, and at 12 months was 98%. These percentages suggest that the conditional dependence model fits less well as the infants grow older, that is, the infants and mothers became less dependent upon the *state of the system*, and more dependent upon one another.

The second step in the data analysis concerning the conditional dependence model was to determine whether the sizes of the NPS were significantly different at the three ages. Prior to that computation, it was necessary to control for the length of the interactions since the interactions were longer at 12 months (M = 11 min, SD = 0.97) and at 4 months (M = 11 min, SD = 2.24) than they were at 6 weeks (M = 7.4 min, SD = 1.88). The t for this effect was 4.405, $p < .000$. A regression analysis was used to remove the effects of session length from the size of the NPS, and the residuals from that analysis were the data used to examine the effects of age on the NPS.

A multiple-regression equation was structured to examine the effects of age on the size of the NPS, such that the first predictor variable was a criterion variable (Pedhazur, 1982) that was generated to take into account within-subject variability that was a function of having the same participants at each age. The second criterion variable was the age of the infant. The analysis indicated a significant age effect [$F(1, 156) = 37.413$, $p < .00$], such that the NPS was significantly larger with age (meaning that the model fit less well with age). These findings indicate that the infants became significantly more contingent when they grew from 6 weeks (mean NPS = 21.27) to 4 months ($t = 3.5855, p < .001$), and from 4 months ($M = 51.63$) to 12 months ($M = 75.69$, $t = 2.280$, $p < .025$; note that these average NPSs have not been corrected for session length).

Response Effect Model

Each response effect (i.e., bias, own sensitivity, other sensitivity, and interaction) was computed for each infant and each mother at each of the infants' three ages. The change in these response effects was observed for each infant from age 6 weeks to 4 months to 12 months. For each of the four response effects, the infants were categorized into four possible groups depending upon the direction of the change: (1) decreasing response effect size at both time intervals (from 6 weeks to 4 months, and from 4 months to 12 months); (2) increasing in the first time interval and decreasing in the second; (3) decreasing in the first time interval and increasing in the second; and (4) increasing in both. In order to test for direction in these measures with time, observed frequencies were compared to equal frequencies—a situation that indicated no time direction. For the infant data, a chi-square test was performed on the frequencies for each response effect and all were significant, leading to the conclusion that there was a direction in the change of these response effects with the increasing age of the infant. The frequency distributions for each response effect and the associated chi squares are presented in Table I.

Analyses of the response effects for the mothers were performed in the same way as for the infants. In the case of the mothers, the interaction response effect was not significant whereas all of the other response effects were. The frequencies and the chi-square statistics are also presented in Table I.

Table I. Frequency Distributions and Chi-Square Statistics for the Change in Response Effects with Age

	Bias	Own sensitivity	Other sensitivity	Interaction
		Infant response effect		
Both decrease	49	52	40	4
Increase/decrease	3	0	9	4
Decrease/increase	1	0	2	11
Both increase	0	1	2	34
Chi square	128.96	151.15	74.47	45.79
p	.000	.000	.000	.000
		Mother response effect		
Both decrease	29	12	30	12
Increase/decrease	7	8	11	8
Decrease/increase	5	9	4	13
Both increase	12	24	8	20
Chi square	26.93	12.28	30.09	5.64
p	.000	.006	.000	.130

Table II. Means and Standard Deviations for the Infant Response Effects as a Function of Infant Age

		Infant age		
Response effect		6 Weeks	4 Months	12 Months
Bias	M	.498	.337	.323
	SD	.025	.097	.068
Own sensitivity	M	.448	.266	.248
	SD	.034	.066	.045
Other sensitivity	M	−.004	−.046	−.050
	SD	.026	.048	.031
Interaction	M	.007	.038	.035
	SD	.016	.045	.026

The means of the response effect and standard deviations of each at each age for the infant data were computed and that information was consistent with the frequency information presented above (see Table II).

The means and standard deviations of mothers' response effects were also computed with results consistent with the frequency data (see Table III).

DISCUSSION

The findings of the present study support the utility of the conditional dependence model as an estimate of contingency in mother–infant interactions, in that it seems reasonable to expect that the infant's interpersonal contingency increases with age. One limitation of the investigation of the question in this study was the examination of two different behavioral systems at 6 weeks and at 4 and 12 months, i.e., infants' visual behavior at 6 weeks and the infant's vocal behavior at 4 months and 12 months. It does, however, seem reasonable to expect that the contingency that occurs with age is across behaviors. As an initial approach to examining the expectation, a subset of 15 interactions were coded for gaze at 4 months. The correlation between the NPS for gaze at 4 months with the NPS for vocal behavior at four months was .42 (p = .06). The analysis of the precise relationship of the development of the two different behavioral modes might be a useful direction for future research.

The interpretation of the response effects model is somewhat more complicated. As detailed in the introduction of this paper, one problem with the model is that the computation of self and other effects do not really separate them as previous investigators have claimed. Second, the estimation

Table III. Means and Standard Deviations for the Mother Response Effects as a Function of Infant Age

		Infant age		
Response effect		6 Weeks	4 Months	12 Months
Bias	M	.557	.514	.496
	SD	.124	.100	.074
Own sensitivity	M	.242	.255	.257
	SD	.052	.047	.038
Other sensitivity	M	−.009	−.031	−.036
	SD	.060	.051	.034
Interaction	M	.011	.018	.019
	SD	.034	.046	.024

of the terms of the model does not appear to exactly correspond to the usual meaning. A third difficulty with the response effects model as tested here (and this is tied to the method of this study and not to the model itself) is the confounding of behavior (gaze vs. vocalization) and age (as was pointed out with the conditional dependence model).

However, the difficulties notwithstanding, the findings of the study indicate age effects for the response effects for both the infants and the mothers (although the age refers to the infants and not to the mothers, it seems unlikely that 10.5 months would be associated with a significant developmental shift in adulthood).

All four of the infants' response effects varied as a function of age. Bias, own sensitivity, and other sensitivity decreased with age and interaction increased with age. In spite of questions regarding terminology in the response effects model, it is clear that both models are measures which reflect maturation when the infants are healthy and well adjusted. As a result they might be considered as baseline information for diagnostic or predictive procedures. For example the apparent decrease in own sensitivity may be an indication of more developed speech patterns, because the more frequent interspersion of sounds with silence in mature speech would lead to a smaller measure than that of infant babbling. Recall that own sensitivity is highest only when involvement follows involvement.

The confounding of structure and function in the estimation of the effects and the labels of the effects is particularly problematic in this regard. For example, one might predict that if the infant becomes more contingent with age, as demonstrated by the conditional dependence model, that own sensitivity might decrease with age and other sensitivity might increase with age. However, inspection of the objective probabilities for those effects does not lead to the same kind of predictions.

In the case of the mothers' response effects, bias and other sensitivity decreased, while own sensitivity increased, and the interaction response effect was nonsignificant. The direction of the effects make somewhat more sense in these analyses. For example, bias seems to be a measure of overall responsiveness. The response effect for bias decreased for the mothers over time, suggesting that the mother responds less as her infant's social responses develop (e.g., as gaze becomes more focused, as the production of noncry vocalizations increases, etc.).

Although the analysis of frequencies for own sensitivity produced a significant test statistic, the direction of change is less apparent. Observation of the change in means shows an increase, but a very small one. One would anticipate consistency of the own sensitivity effect if it is a measure of intraindividual stability. Other sensitivity may be a kind of politeness effect (taking a negative value if one never speaks when the other is involved).

Mothers became more "polite" (as indicated by lower average other sensitivity effects) over time, suggesting that they were increasingly allowing their infants to "have a turn" in the interactions.

Although the application of mathematical models to the understanding of infant social behavior is still in its early stages, continued research in this area seems worthwhile. For example, the models used here operationalized dialogic behavior in terms of on–off states that occurred each quarter of a second. The behavior could also be measured applying speaking turns. Time series regression analysis is a useful tool for such study.

The response effects measures were calculated as unweighted averages of conditional probabilities (e.g., q_0 was the proportion of time that mother spoke given that both were silent). It may also be useful to observe the averages weighted by the proportion of the dialogue spent in each of the states. In that case, the weighted bias value would be the proportion of the conversation in which the individual was involved, but weighing the other three measures might produce more useful results.

Important further tests of the usefulness of the quantities described here will be their ability to predict conventional measures of development in tests of convergent and discriminant validity.

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