CHAPTER 10

MODELING INTERPERSONAL COORDINATION DYNAMICS: IMPLICATIONS FOR A DYNAMICAL THEORY OF DEVELOPING SYSTEMS

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A significant aspect of development is that it occurs in a social context (Lockman & Hazen, 1989). The presence of other people and their role in the first years of our lives are so natural and omnipresent that it is easy to overlook the intricacy of the interpersonal coordination that must develop. The reason underlying this oversight is perhaps the unilateral nature of the coordination behavior in early caregiver/infant actions (i.e., caregiver-implanted). However, as the infant develops a motor repertoire, the coordination goals necessarily become more mutual (as any parent can attest) and the intricacy of coordination involved becomes more obvious. The basis for the ensuing social coordination that develops is necessarily interpersonal motor coordination. The early dyadic activities of conversation and play are necessarily spatially and biomechanically constrained. For example, in order for child and adult to converse, or play pata-cake or peek-a-boo, there must be a coordination of the direction of gaze (Fogel, Nwokah, Hsu, Dedo, & Walker, 1993) if not limbs.

The goal of this chapter is to demonstrate how the development of interpersonal coordination might be modeled. In particular, it will examine whether the theory and method of the dynamical systems perspective used in the study of adult interpersonal motor coordination can be used to model the development of interpersonal coordination. One problem that needs to
be overcome to successfully model any developing system is the degree of variability in the intrinsic functioning of such a system. That is, obviously, initial attempts at producing a movement pattern will be characterized by failures and half-successes. In principle, such variability could hamper attempts at providing an explicit formal model of a coordination behavior. A subsidiary goal of this chapter is to demonstrate that the dynamical systems perspective is sufficiently rich to model such systems in spite of the variability observed. In brief, the unstable behavior produced should have predictable characteristics if a dynamical control regime is underlying it. After an overview of dynamics and development, methods used for the dynamical study of interpersonal adult coordination are reviewed. How the problem of behavioral variability is overcome in this domain is edifying for dealing with developmental behavioral variability. The application of these methods to a developing interpersonal coordination is then proposed.

DYANMICS AND DEVELOPMENT

Dynamical theory is used to model a physical system's properties of stability and change. It is a general theory that can be applied to physical systems whose behavior occurs at many space/time scales. Historically, it was developed to model the cosmological behavior of planets and galaxies (Eckeland, 1988), but more recently the understanding of the abstract, qualitative nature of dynamics has led researchers to apply these methods to complex systems at the chemical, biological, and social scales (Haken, 1977; Kugler & Turvey, 1987). The idea underlying these more recent applications is the fact that the complex systems are open systems—they are affected by flows of energy and information from their environment—and depending on their current relation to their surroundings they may take on different organizations. The goal is to mathematically model the organization of these systems (i.e., their stabilities) and their reordering under certain influences (i.e., their change). Importantly, dynamical theory provides a framework of methods that allow for the proposal of formal models that make predictions about the nature of physical systems' stabilities and change. Additionally, such formal models lead in a fairly straightforward manner to empirical tests of dynamical models.

Given dynamical theory's ability to model the reordering of physical systems, one can see why it has appealed to those investigating developing behavioral systems. Developing behavioral systems change in ontogenetic time. Described dynamically, one stable behavioral organization (e.g., walking in a toddler) "emerges" from another stable pattern (e.g., crawling in an infant). Understanding this process of behavioral change has a number of subsidiary questions. How can one understand what defines a behavioral stage? How can one understand the transition to a new one? What are the proximal causes for such a transition? Dynamical theory provides a general template for investigating emerging states in a physical system and, consequently, for understanding how these questions can be answered. Further, dynamical theory is general enough to model developmental change of systems that have different complexity or scale: The promise of dynamical theory is that single-organism behavioral development as well as interorganism behavioral development can be modeled using similar methods.

The foundational concept underlying the dynamical modeling of a complex open system is that of an order parameter (Haken, 1977). In brief, an order parameter is a measurable property that summarizes the quality of the organization of the system. It defines a metric whose values demarcate the qualitative states of system order. The measurement of the order parameter allows one to determine the mean state of the system and, by measuring the variability of the order parameter, the stability of that state. Of interest is how the mean and variance of the order parameter are influenced by external properties, namely, control parameters, that affect the state of the system. Perspicuous control parameters effect a weakening of a system's stable state, which often leads to the system's transition to a new stable state. The sudden quality of these transitions and their nonlinear rate of change has led them to be called phase transitions (Haken, Kelso, & Bunz, 1985) or catastrophes (Gilmore, 1981).

The now classic illustration of a dynamical model of a behavioral system is in found in interlimb coordination. Interlimb phasing has two natural modes. Limbs can be easily coordinated so that they are at the same place in the cycle at the same time—the in-phase mode or 0° relative phase—or so that they are in opposite places in the cycle at the same time—the antiphase mode or 180° relative phase. The two relative phase modes have been found to be differentially stable: The antiphase mode is less stable than the in-phase. The bimodality and differential stability of bimanual phasing have been observed in experiments where the 180° mode breaks down at higher frequencies of oscillation whereas the 0° mode does not (Kelso, 1984; Schmidt, Carello, & Turvey, 1990) and in experiments that measure the degree of steady-state fluctuation of the two modes (Schmidt, Shaw, & Turvey, 1993; Turvey, Rosenblum, Schmidt, & Kugler, 1986).

These properties have been explained as being a consequence of the dynamical nature of the control structure underlying bimanual coordination. The limb effector system acts identically to a regime of two coupled oscillators where the coupling strength between the oscillators decreases with increasing frequency. Haken et al. (1985; Schöner, Haken, & Kelso, 1986) employed a coupled oscillator regime with point attractors at relative phase angles of 0° and 180° to model the bimanual phasing properties. The dynamical description of relative phase angle (\(\theta\)) between the two rhythmic units is defined by the differential equation:
\[
\dot{\phi} = \frac{dV(\phi)}{d\phi} + \sqrt{Q\epsilon}
\]  

(1)

where the rate of change of the relative phase angle \( \dot{\phi} \) is a function of the rate of change of the potential function,

\[
V(\phi) = -a \cos(\phi) - b \cos(2\phi)
\]  

(2)

and a stochastic noise term \( \epsilon \) of magnitude \( Q \). The minima of the potential function (where its rate of change is 0) indicate the stable relative phase patterns attainable by the coupled oscillatory regime. Figure 10.1 demonstrates that these stable points of the regime appear at the function minima of \( \phi = 0^\circ \) and \( \phi = 180^\circ \), and that the stable point at \( \phi = 180^\circ \) is less stable (i.e., more shallow) than that at \( 0^\circ \). If one assumes that the ratio of the coupling strengths \( b/a \) decreases with increasing frequency, the steady state at \( \phi = 180^\circ \) (i.e., the local minimum of the equation at \( 180^\circ \)) disappears when \( b/a \) reaches a critical value of .25. The scaling of the control parameter leads to a weakening of the stable state at \( \phi = 180^\circ \). Hence, under the assumption that the coupling strength ratio decreases with increasing frequency, this coupled oscillator dynamic predicts both the bimodality and differential stability observed in bimanual limb phasing.

The cause underlying the behavioral change in this interlimb phasing example is a combination of the weakening of the attractor at \( 180^\circ \) (because of decreasing coupling strength) and the stochastic fluctuations (i.e., \( \epsilon \)) that precipitate the new stable state. This is a general principle of dynamical control processes, namely, that variability is a natural part of systems that change behavioral mode and that fluctuations can lead to the exploration of new modes (Beek, 1989). The ramification of this point for modeling developing behavioral systems is obvious: Developing systems should be noisy because they are changing modes.

An example of the use of dynamical theory to understand the development of coordination is the ground-breaking research of Esther Thelen. In a series of studies (Thelen & Fisher, 1982; Thelen & Ulrich, 1991), Thelen and colleagues investigated infant leg movements that are the precursors to walking. She noted that interlimb leg movements performed on treadmills were coordinated early on, lost coordination for a time, and then regained it. She provided evidence that this emergence and loss of coordination can be explained as the behavior of a dynamical action system being scaled by changes in body weight—that is, body weight is functioning as a control parameter. In the early stage, the muscle tone of the infants’ legs is great enough to rhythmically phase the limbs in a coordinated fashion. However, as the infant gains weight, the strength of the legs is no longer enough and coordinated interlimb phasing disappears. Finally, as the infant becomes more active and muscle tone improves, coordinated interlimb phasing re-appears. In more recent work, Corbetta and Thelen (1994) studied the dynamical basis of changes from bimanual to unimanual reaching in first year of life. Their work demonstrates that the development of reaching involves the control of the activity of the contralateral arm: Initially the two arms are strongly coupled, and later they can be controlled independently. Thelen’s research highlights that in order to understand the development of coordinated movement patterns, one must study more than the kinematics of limbs—namely, the dynamical “cooperative coupling of ensemble components” involved and how nonspecific properties can function as control parameters that change the modes of equilibrium of the cooperative coupling.

Although the past application of dynamical systems theory to developing systems has been quite promising, it has been metaphoric in nature, has lacked the formal modeling found in the adult interlimb phasing investigations, and consequently the interaction of prediction and experiment that a mathematical model can afford a research program. One reason that has prevented the use of formal models is that such models generally represent steady-state or stationary behavior, and developmental systems by their very nature produce behavior that is not steady and is nonstationary. So,
for example, Equation 1 represents a dynamical system with steady-state behavior near 0° (in-phase) or 180° (antiphase) and temporary transitory behavior from the 180° steady state to 0° steady state. But in studying the leg kick precursors to walking in infants, one may see a somewhat arbitrary switching back and forth between these and other relative phase relations. And because this is naturalistic research with young infants, an experimenter cannot implement steady-state task constraints on the behavior, nor would the experimenter want to because that would obviate the naturalistic research questions (e.g., what are they doing at what developmental stage). Not only do the formal models as typically rendered not predict the nonstationary behavior of developing systems, typical methods of measurement are thwarted as well: Stationary statistical measures such as the mean and standard deviation are unenlightening summaries of the nonstationary patterns of behavior exhibited by developing systems or any system where the behavior is less stereotyped.

However, as we argue, nonstationarity of an order parameter alone does not require abandoning dynamical models. Indeed, dynamical models make predictions about what form the nonstationary behavior should take. To demonstrate this point and the methods of analysis of nonstationary relative coordination, we review research investigating adult between-person coordination.

THE DYNAMICS OF INTERPERSONAL INTERLIMB COORDINATION

Interpersonal interlimb coordination can be described on a continuum of task constraint. On the one hand, there are interpersonal coordinations such as in dance and in sports that are strongly task constrained in that the coordination is much practiced and has an explicit goal. Such coordination is intentional. On the other hand, there is interactional synchrony found in natural social interactions (e.g., conversations) that is only weakly constrained by the occurring task and is often unintentional. Research in social psychology (Newstoun, Hairfield, Bloomingdale, & Cutlina, 1987) suggests that there is a natural tendency for individuals to synchronize their movements without intending to, especially when the two individuals are either genetically or rapports bound (Bernieri, 1988; Bernieri, Reznick, & Rosenthal, 1988). This interlimb coordination occurs in conversation, between listener and lecturer, or in mother-child play. In interactional synchrony then, the coordination is implicit in another more explicit goal (e.g., sharing information in a conversation).

Although it has been proposed that interpersonal interlimb coordination across the task constraint continuum can be explained by dynamical proc-

esses of self-organization, past research has only explicitly tested this hypothesis in strongly constrained tasks in which intentional coordination is the goal. Such interlimb coordination is amenable to experimental investigation and formal dynamical modeling because the experimenter dictates the coordination pattern to be maintained. Hence, the order parameter that has been used to evaluate interlimb coordination, relative phase is, for the most part, stationary under typical parameterizations. To use von Holst’s (1939/1973) terminology, the stationary relative phasing in such interlimb coordination represents absolute coordination. However, the problem of nonstationary coordination arises in trying to model the unintentional interlimb coordination between individuals in situations where the task constraint is weak. Through statistical (Condon, 1982) and perceptual measures (Bernieri et al., 1988), the analysis of such interactions reveals that individuals are entrained, albeit weakly. However, no one coordination pattern is apparent in these interactions, and hence the relative phasing is not centered around a constant value. Consequently, the variability of the coordination pattern is high and the mean states of this order parameter are not measures of equilibrium states. Indeed, the coordination system does not seem to be in a steady state at all. Therefore, as with developing systems, the standard methods of formal dynamical modeling are thwarted.

Kelso and colleagues (Kelso & Ding, 1994; Zanone & Kelso, 1990) pointed out that non-steady-state coordination behavior (what von Holst, 1939/1973, called relative coordination) can be produced by dynamical systems with weak attractor basins and intrinsic noise. Such dynamical systems demonstrate the property of intermittency: a constant change in state with an attraction to certain regions of their underlying phase space. Hence, it is possible that dynamical systems that demonstrate intermittency can in principle be used to model the noisy nonstationary behavior seen in weakly coupled systems such as naturally interacting dyads or developing interlimb control structures. In what follows, we review how intentional interpersonal coordination can be dynamically modeled using an intrapersonal coordination experimental paradigm and standard methods of dynamical modeling, and then demonstrate how the paradigm and dynamical model can be adapted to explore the nonstationary relative phasing of unintentional interpersonal coordination.

Intentional Interpersonal Coordination

The standard method that has been used to dynamically model interlimb coordination is to measure how coordinative mean states (e.g., of relative phase) and their variability change as external control parameters (e.g., frequency and inertial loadings of limbs) are manipulated. Interestingly, studies using this strategy for investigating intentional interpersonal coo
dination have demonstrated dynamical coordinative processes that are identical to those found in within-person coordination. Schmidt and Turvey (1994) used a rhythmic coordination paradigm previously used to investigate within-person coordination (see Kugler & Turvey, 1987) to evaluate intentional interpersonal interlimb coordination. In this methodology, two participants sitting side by side oscillated a weighted dowel (called a wrist-pendulum) in the sagittal plane using unlar and radial flexion of their wrist (Fig. 10.2). What is manipulated is the differential inertial loading of the two wrist-pendulum systems. The two wrist-pendulum systems could be identical or different in their mass and length magnitudes. Such an inertial manipulation effectively scales the preferred frequency (eigenfrequency) of the oscillatory wrist movements (Kugler & Turvey, 1987; Turvey, Schmidt, Rosenblum, & Kugler, 1988), and the difference of the loadings between the two wrist-pendulum systems manipulates the difference between the preferred frequencies or the eigenfrequency difference of the pendulum pair. It is this property, the eigenfrequency difference, that has been used as an effective control parameter to manipulate order parameter (relative phase) dynamics.

Previous studies investigating the coordination of wrist-pendulums across the two wrists of a single person (see Schmidt & Turvey, 1995, for a review) investigated whether the steady-state (i.e., no frequency scaling) relative phasing of the wrist-pendulums would exhibit the predicted characteristics of a coupled oscillatory dynamical system such as that which had been used to model the breakdown of relative phasing (Haken, Kelso, & Bunz, 1985). That dynamical model predicts two properties if the eigenfrequency difference of the two oscillators is scaled. The first is fixed-point (attractor location) drift, which means that the mean relative phase exhibited by the oscillatory system moves away from the canonical values of 0° (for in-phase) and 180° (for antiphase coordination) in proportion to the eigenfrequency difference. Second, the model predicts that as the magnitude of the eigenfrequency difference increases, the stability of the system should decrease and fluctuation of the order parameter should increase. Both of these predicted dynamical characteristics have been affirmed in numerous intrapersonal wrist-pendulum paradigm studies (Schmidt & Turvey, 1985) supporting the hypothesis that control structures underlying the steady-state coordination of interlimb rhythmic movements within a person have a dynamical basis.

Schmidt and Turvey (1994) asked the related question of whether the dynamical principles involved in the intrapersonal coordination of rhythmic movements across the central nervous system (CNS) were sufficiently general to operate in the intentional visual coordination of movement between two people. In this study, three pairs of participants were told to visually coordinate the oscillations of their wrist-pendulums at a comfortable tempo in antiphase. Sixteen different wrist-pendulum pairs were used per participant pair. An exemplary relative phase time series (\(\phi\)) from a typical trial is plotted in Fig. 10.3. Because the relative phase is centered around a mean value of about 180°, one can tell that a stable antiphase coordination was performed for the entire trial, yielding stationary relative phase time series. The coordination here is absolute coordination, and hence the mean state of the order parameter and its variability can reliably be used to determine whether the dynamical model predictions are affirmed. Summary graphs of these measures are depicted in Fig. 10.4. The left-hand graph demonstrates fixed-point drift, the drifting of the attractor location. As the eigenfrequency difference (\(\Delta\omega\)) of the pendulum pair is scaled away from 0, the mean relative phase of the system (\(\phi\)) moves away from 180° such that the pendulum with the inherently faster eigenfrequency is leading in its cycle. The right-hand graph demonstrates the decreasing stability (increasing fluctuation) of the coupled oscillatory system as the eigenfrequency difference is scaled away from 0.

This study suggests that intentional interpersonal coordination can be understood in terms of the same dynamical processes of self-organization that underlie the coordination of limbs across the CNS. When two people intend to coordinate their rhythmic limb movements, the ensuing behavioral pattern is that of a dynamical coupled oscillatory system. It appears that

![Fig. 10.2. The experimental arrangement used for studying interpersonal interlimb coordination.](image)

![Fig. 10.3. A stationary interpersonal relative phase time series from an intentional coordination experiment (Schmidt & Turvey, 1994).](image)
the participant pair has assembled a dyadic coupled oscillatory control structure to maintain their coordination.

**Unintentional Interpersonal Coordination**

The question remains, however, of whether natural interpersonal coordination where synchronous coordination is not an explicit goal has a dynamical basis. Although this suggestion has been made and metaphorical dynamical explanations have been given (e.g., Newtson et al., 1987), no formal dynamical modeling of interactional synchrony has been forthcoming. To be redundant, the problem with providing such a model is that, unlike intentional coordination where the experimenter dictates a particular coordination pattern to be maintained, the coordination pattern in unintentional coordination is not constant, and consequently, the order parameter used to evaluate interlimb coordination, relative phase, is nonstationary. This nonstationarity disallows the standard methods of dynamical modeling: the use of mean states and their fluctuations to determine attractor states and their strength (respectively). However, nonstationarity is expected of a dynamical system if its attractors are weak and the system contains a degree of inherent noise. What is needed are new methods of analysis to evaluate the nonstationary behavior to determine whether it indeed demonstrates intermittent attraction to weak equilibrium regions, that is, whether the coordination behavior demonstrates intermittency.

In particular, what needs to be investigated in unintentional interpersonal coordination is whether rhythmic movements are drawn to the relative phases of 0° and 180° that are indicative of the stable modes of the coupled oscillator dynamic underlying intentional interpersonal interlimb coordination. In order to investigate this, an experiment was performed that attempted to capture unintentional interactional synchrony in the laboratory though an adaptation of the wrist-pendulum paradigm previously described. Ten pairs of participants were recruited from undergraduate psychology classes to serve as subjects. The pairs sat facing the same direction and oscillated hand-held pendulums in the sagittal plane. The subject task was different for the two halves of a trial. During the first half of a trial, subject pairs were instructed to look straight ahead so that they could not see one another and to swing the pendulum at a comfortable rate that they could "perform all day." During the second half of a trial, subjects were told to look at the other subject's moving pendulum but maintain their preferred tempo from the first half of the trial. Each subject performed thirty 24-sec trials. The angular excursions of the two pendulums were collected and from these the time series of continuous relative phase was calculated (see Schmidt & Turvey, 1994, for calculation procedures). Of interest was whether on the second half of the trials (when visual information was available) the subjects would tend to entrain their movements unintentionally and whether this coordination is constrained by coupled oscillator dynamics that seem to guide intentional interpersonal coordination.

Inspection of the relative phase time series in Fig. 10.5 suggests no superficial difference between the first and second parts of the trial. If there is any entrainment in the second half of the trial, the coordination is not absolute but relative coordination. Compared to the Fig. 10.3, the relative phase measure is not centered around a constant value but is constantly changing through all possible states. It is, therefore, nonstationary. The mean and variance of relative phase would not in this case be revealing about the prospective underlying dynamical mechanisms. However, if there

![Fig. 10.4. Model predicted results from visual intentional interpersonal coordination experiment (Schmidt & Turvey, 1994): Fixed-point drift (left: \( r^2(1.14) = 85, y = 0.17x + 0.05, p < .001 \)) and decreasing system stability (right: \( r^2(1.14) = 47, y = 0.04x^2 + 0.04x + 2.3, p < .02 \)) as functions of the eigenfrequency difference (\( \Delta f \)) of two visually coupled wrist-pendulum systems (see text).](image)

![Fig. 10.5. A nonstationary interpersonal relative phase time series from an unintentional coordination experiment. In the first 12 sec of the trial, the participants were not visually coupled—they oscillated their pendulums not looking at each other. In the second 12 sec, the participants looked at the other person's pendulum but attempted to maintain their own preferred tempo.](image)
is a weak dynamical coupling of the two movements yielding unintentional entrainment, one should be able to see evidence of intermittency. That is, if a coupled oscillator dynamic is constraining the behavior observed, then an attraction to the relative phases defined as fixed points for intentional interpersonal coordination (namely, 0° and/or 180°) should occur in the second half of the trial.

This intermittency of attraction can be evaluated in a number of ways. First, attraction to the fixed points in the second half of the trial should be indicated by a distribution of relative phase angles near the attractors at 0° and 180° that represents the dwell time in the attractor basin. Relatedly, because the rate of change of the relative phase (Δφ) should slow down in the part of the trial that exhibits the intermittent attraction, Δφ should be less and should in particular decrease near the 0° and 180° fixed points in the second half of the trial.

To determine whether there was a greater concentration of φ near 0° and 180° in the second trial half, the φ time series (Fig. 10.5) were normalized into the 0–180° range. The number of relative phase values that fell within the nine 20° phase regions between 0° and 180° was calculated for each trial half. As anticipated, Fig. 10.6 (top) demonstrates that the distribution of relative phase is flat for the first trial half but has greater concentrations around 0° and 180° compared to the middle phase regions in the second trial half when visual information was available. Pairwise t-tests comparing the proportion of relative phases in each phase region reveal that the second trial half has significantly greater relative phases near 0° [0° to 20°: \(t(299) = 6.25, p < .001\); 20° to 40°: \(t(299) = 2.33, p < .05\)] and significantly fewer in the phase regions between 0° and 180° [60° to 80°: \(t(299) = 4.42, p < .001\); 80° to 100°: \(t(299) = 5.00, p < .001\); 100° to 120°: \(t(299) = 5.63, p < .001\); 120° to 140°: \(t(299) = 3.01, p < .01\)]. The concentration of the second trial half was not significantly greater or less near 180° [140° to 160°: \(t(299) = 0.42, p > .05\); 160° to 180°: \(t(299) = 0.03, p > .05\)], however. These results suggest an attraction to the 0° region and a repulsion from relative phase angles between 0° and 180°. The lack of attraction from 180° can mean that either no attractor was present or that, if present, its attraction was too weak to be verified. In sum these findings can be interpreted as prima facie evidence for the existence in nonintentional interpersonal coordination of a coupled oscillator dynamic that produces fairly strong intermittent attraction to 0° and a weaker or nonexistent intermittent attraction to 180°.

Intermittent attraction can also be measured using a related index of attraction, Δφ. If the two rhythmic movements periodically become entrained or phase locked, the rate of change of the relative phase (Δφ) should decrease. In order to evaluate this possibility, the Δφ time series was calculated as \(\phi_{n+1} - \phi_n\) (using the normalized φ time series). The results demonstrate that, indeed, the average Δφ was less for the second part of the trial.

**FIG. 10.6.** Model-predicted intermittent attraction from an unintentional interpersonal coordination experiment. The rate of change of relative phase (Δφ) slows down near the 0° and 180° attractors of the Haiken et al. (1985) model (bottom) only when visual information is available about the other's movement (second trial half). Relatedly, this intermittent attraction results in a greater frequency of occurrence of relative phase angles in these attractor regions (top).
than the first (3.97 vs. 4.83 °/sec), suggesting a slowing down of the relative phase change when visual information was available. To determine whether the decrease in relative phase was near the 0° and 180° attractor locations, the average Δθ was calculated as the relative phase passed through nine 20° relative phase regions between 0° and 180°. These mean rates of change across these regions for each trial half appear in Fig. 10.6 (bottom). The rates of change show no pattern across the relative phase regions for the first trial half. But for the second trial half, an inverted U-shape plot is revealed with minimum rates of change near 0° and 180°, which suggests that the system was being attracted to these regions. Pairwise t-tests comparing Δθ for each trial half revealed no significant differences (p > .05), however. The power of these tests may have been severely hampered by the variability associated with the Δθ time series.

The patterning of results portrayed in Fig. 10.6 suggests that an intermittent attraction can occur in unintentional interpersonal coordination at the attractor locations of a coupled oscillatory regime. It seems that "ghosts" of the attractor landscape used in intentional coordination behavior also constrain unintentional entrainment behavior and suggest that the mere presence of an information linkage without an explicit intention to coordinate is sufficient for the operation of these dynamical principles of self-organization. The methodological importance of these analyses is that in spite of the nonstationarity of the coordination order parameter, the dynamical basis of the variable behavior patterns can be resolved and predictions from a formal dynamical model can be made about the structure of the nonstationary behavior. The point is that one must move away from the standard measures of the coordination (order parameter) dynamics (i.e., means and variance) and look at the structure of the variance for signs of intermittent attraction. In brief, different methods are necessary for investigating coordination systems that by their very nature display variable behavior. Further, these methods can be applied to any system that has been proposed to have a dynamical basis, whether the system has variable behavior because it is complex (e.g., a social system) or has variable behavior because it is evolving (e.g., a developing system). In the next section, we distill from the preceding review of interpersonal coordination methodological steps necessary for studying the development of interpersonal coordination between a mother and infant.

DYNAMICAL MODELING OF DEVELOPING INTERPERSONAL COORDINATION

Recent work by Alan Fogel and colleagues (Fogel et al., 1993) investigated the role of posture and reaching in mother-infant interaction. It has been previously established that such interactions with very young infants (2–4 months) consist of predominantly mother-infant face-to-face gazing—mutual gazing. As the infant matures and becomes interested in inanimate environmental objects, facing away from the mother—away gazing—becomes an alternative behavioral mode.

Fogel et al. (1993) were interested in what sensorimotor factors precipitated the transition between these two developmental stages. One factor they found was the direction of the gaze of the infant. They found that mothers shifted the infant's position more when the infant was gazing away from them. Eventually as the infant matured, these mother-induced postural shifts were in the direction of the infant's gaze (i.e., away from the mother). Interestingly, the spatial relation of mother and infant in the face-to-face interaction is coconstructed—both mother and infant are involved in producing the final state. Another sensorimotor factor underlying the transition between these two developmental stages is the onset of reaching behavior. In some of the infants the match between gazuing away and the mother's facing them away did not occur until after they began to reach. Hence, for these infants, their nonmother directedness was not substantially recognized in the dyadic system until the infant was able to have manual interactions with the surroundings.

Fogel et al. (1993) interpreted the development of this behavioral mode from the dynamical perspective. The coconstructive nature of the behavior—the fact that there is a mutual influence between the components of a system—is characteristic of a dynamical system. Fogel et al. (1993) suggested that "the dyadic match between infant gaze away and maternal holding of the infant facing away...possibly (represents) a social attractor state...which...must wait the ontogenetic emergence of at least two control parameters: (1) gazing away and (2) reaching" (p. 418). In this final section, we would like to suggest a modeling procedure based on the methods introduced to investigate adult unintentional interpersonal coordination that can be used to support the hypothesis that these mother-infant behavioral modes have a dynamical basis.

Qualitatively, the dynamical system that would produce these modes of interpersonal gaze is one that would have one attractor early (2–4 months) (representing the coordination pattern of mutual gaze) and two attractors later (representing the possible coordination patterns of mutual gaze and away gaze). The dynamical landscape of such a system can be represented by the potential functions in Fig. 10.7 (bottom). (Although the modeling here will be strictly qualitative, an explicit quantitative function representing these potential functions can also be provided.) Assuming that these attractors exist, what behavioral predictions can be made? What measurements can we make of the behavior to verify the existence of these interpersonal attractors?

The first step is to define an order parameter—a property that summarizes the quality of a coordinative state of interest. This step was tacti in
relative gaze must be acquired. It can be obtained by placing movement recording cameras (e.g., of a Peak Performance or Optotrak movement analysis system) on the ceiling to obtain the change in positions (i.e., the position time series) of the mother’s head and the infant’s head. Both front and back head positions would need to be acquired in order to determine the direction of gaze from the time series. The angle of relative gaze can be calculated from these head position time series. As for the experimental procedure, the natural 5-min interaction task used by Fogel et al. (i.e., have the mother sit in a chair for 5 min and play and talk to the baby as they would at home) would produce time series of sufficient length for a dynamical analysis.

Given the naturalistic task, one should expect the time series of relative gaze to be nonstationary. In terms of the dynamical landscape of Fig. 10.7 (bottom), the noise in the system (defined as forces coming from an external frame of reference) is so great that the system’s state is pushed from the equilibrium positions at the bottom of the attractor wells. In spite of this nonstationarity of the order parameter, if interpersonal attractors for the behavioral modes of mutual gaze and away gaze exist, one should see intermittent attraction towards the values of \( \rho = 0 \) and \( \rho = 180^\circ \). Hence, after the order parameter has been defined and an experimental setup to measure it devised, one can use the methods described in the interperson section to determine whether an intermittency of attraction occurs in the requisite portions of the dynamical landscape.

To do this one should first plot the distribution of the order parameter across the range of \( 0^\circ \) to \( 180^\circ \) to determine whether the states of the system are concentrated near the proposed attractor basins. If the interpersonal system indeed represents a social attractor state, then at early ages, one should see the relative gaze angle concentrated around \( \rho = 0^\circ \), and at later ages, one should see the relative gaze angle concentrated around \( \rho = 0^\circ \) and \( \rho = 180^\circ \) (Fig. 10.8). Second, the mean rate of change of the order parameter, \( \Delta \rho \), should be calculated for different relative gaze regions (e.g., \( 20^\circ \) intervals.

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**Fig. 10.7.** The definition of the order parameter (top) proposed for investigating the coordination in mother-infant interaction and its development—the angle of relative gaze. The attractor landscapes (bottom) proposed to dynamically model the early (< 2 month) and later mother-infant relative gaze patterns (see text).

**Fig. 10.8.** Model predictions of the distribution of relative gaze angles for early (<2 month) and later mother-infant interaction if interpersonal attractors are underlying these coordination patterns.
between $0^\circ$ and $180^\circ$). $\Delta \rho$ can be calculated as $\rho_{m1} - \rho_n$. If the $\Delta \rho$ decreases near $\rho = 0^\circ$ for younger ages and near $\rho = 0^\circ$ and $\rho = 180^\circ$ for older ages, then this is additional evidence of intermittent attraction—the gaze relation tends to slow down at these relative angles at these different ages. If $\rho$ and $\Delta \rho$ are patterned in the predicted ways, then there is empirical support for interpersonal attractors underlying gaze direction in mother–infant interaction.

Having quantitatively captured the coordination dynamics has the added benefit that an index of the strength of the attractors can be calculated. The strength of the attractor is inversely related to the $\Delta \rho$ in the attractor region (i.e., the smaller the rate of change, the stronger the attractor). This measure would be useful in a number of ways because it quantifies the strength of a behavioral mode. First, this measure would provide a dynamical means of comparing the behavior of the different subjects and would provide a basis for grouping them into developmental stages. Second, this measure would provide a means of determining whether a given property is indeed functioning as a control parameter. Fogel et al. (1993) proposed that the infant abilities of gazing away and reaching operate as control parameters. One would expect to see a high correlation between the strength of a new behavioral mode and a quantitative index of a property (e.g., gazing away) whose change is underlying the emergence of the new behavioral regime.

10. INTERPERSONAL DYNAMICS

behavioral transitions (Schmidt & Turvey, 1995). Although transitions between stages in development are important to understand, they are difficult to investigate given individual differences in development and the slow time scale of their evolution. The suggestion made here is to first verify the dynamical basis of stable (or not so stable) modes. As demonstrated earlier, this can be achieved by determining whether these modes exhibit the characteristic properties of attraction. Using the steady-state analysis of the behavioral modes as a basis, one can then turn to investigating the transition between two developmental states as dynamically based change.

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REFERENCES


CONCLUDING REMARKS

Developing systems are characterized by their change and the inherent variability of their behavioral patterns. Nonstationarity of the coordinative patterns are the rule rather than the exception. The dynamical system perspective offers a very rich set of concepts for modeling stability and change in physical systems. We have tried here to demonstrate, using our work on adult interpersonal coordination, that systems that exhibit very variable, nonstationary coordinative patterns can be dynamically modeled, as well as those that exhibit more stereotyped behavioral patterns. We have tried to demonstrate how the intermittent attraction found in weak dynamical systems can be a characteristic property of such nonstationary coordinative systems.

Using the Fogel et al. work on mother–infant interactions, we have proposed how this kind of dynamical system can be used in the study of inherently variable interpersonal developing systems. However, this method can also be used by developmental researchers to study the development of interpersonal interlimb coordination (for an example of the development of clapping see Fitzpatrick, chapter 3, this volume). One theme of the method revealed here is an emphasis on modeling behavioral stabilities rather than