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Developmentalists are generally interested in systems perspectives and this is reflected in the theoretical models of the past decade. However, the methodological tools to test these models are either nonexistent or difficult for many researchers to use. This article reviews the state space grid (SSG) method for analyzing synchronized event sequences based on dynamic systems (DS) principles. Following a review of these DS concepts and the basics of the SSG method, several studies are reviewed. Greater emphasis and detail are provided for three longitudinal studies that relate real-time socioemotional dynamics to processes of developmental change and stability. The concluding sections provide guidelines for researchers interested in using the SSG method and some suggestions for future SSG studies.

Keywords: development; dynamic systems; methodology; state space grids

It has become fairly common for developmentalists to take at least a partially systemic view of children's development. The idea that a child is nested within a family, which is nested within a culture, for example, is not controversial. Indeed, methods that can partition variance into these various levels, such as multilevel modeling, have been quite useful in testing some models of developmental change. However, it is not just the macro social structure that is hierarchically nested; development is a process that is hierarchically nested in *time* (Granic, 2005). Early experiences that occur moment-by-moment become the building blocks of patterns, habits, and traits later on. The process of synaptic change provides a useful heuristic by which we can understand this temporal process. Synaptic pruning is the result of repeated experiences that literally shape the neuronal structures through which future experience is processed. Thus, events that occur in real time create structures over developmental time and these structures then constrain subsequent real-time processes (Lewis, 2005). Of course, this occurs at the neuronal level as well as at the behavioral level. For example, a child's interactions with caregivers shape her social and emotional habits. Over time, interpersonal patterns form and stabilize making it increasingly unlikely that other patterns could emerge. Again, this is not a controversial description of development. The problem is that we do not have adequate or accessible methods with which to describe and analyze behavioral processes as they occur within a developmental context. I present here one method that incorporates time as a dimension of analysis, the state space grid (SSG) technique, in which both real-time and developmental-time processes can be related. In the next section, I review dynamic systems (DS) concepts upon which this method is based. Then, I review studies that have used this method to date. The final section describes several ways that this technique can be used.

Dynamic systems and development

Over the past few decades, there has been an increasing interest in systems views of development (Bergman & Magnusson, 1997; Bronfenbrenner, 1979; Fogel, 1993; Ford & Lerner, 1992; Gottlieb, 1991; Granic & Patterson, 2006; Lewis, 2000; Thelen & Smith, 1998; van Geert, 1994). All of these theoretical approaches provide rich descriptions of a nested, hierarchical organization of developmental factors that range from a micro-level (e.g., neuronal structure and function) to a macro-level (e.g., social context). However, the description of a nested hierarchy does not necessarily reveal the temporal processes that occur both within and between these levels of organization. One set of systems-oriented developmentalists have thus turned to what has been learned in physics, mathematics, biology, and other sciences about some universal properties of complex, adaptive, open systems. These views can be identified as the dynamic systems (DS) approach to development. DS concepts such as self-organization, attractors, state space, and phase transitions have been parsimoniously applied in several models of developmental phenomena (Fogel, 1993; Granic & Patterson, 2006; Lewis, 2005; Thelen, Schoner, Scheier, & Smith, 2001; van Geert, 1998). The basic premise is that DS principles account for properties of all dynamic, open systems and therefore, if we assume that the human individual, dyad, or group is a dynamic system as well, these principles can also account for human behavioral patterns.[1] Thus, DS concepts provide a conceptual framework with which to understand the *processes* of development. Several of these

[1] It should be noted that there are generally two camps of DS developmentalists: those who claim that only a system of equations is the dynamic system (e.g., van der Maas, 1995), and those who begin with the assumption that the individual, dyad, or group *is* the dynamic system that can be described in various ways including via equations (e.g., Granic & Hollenstein, 2003). The approach described here is from the latter perspective.

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concepts that are directly relevant to the SSG method described in this article are briefly reviewed next, although the reader is encouraged to consult more detailed reviews (Granic & Hollenstein, 2003; Lewis, 2000; Thelen & Smith, 1998; van Geert & Steenbeck, 2005).

A system can only be in one state[2] at any moment in time, even though many different states may be available. The dynamics of a system are the changes from state to state over time. In DS terms, the range of all possible states is called the *state space*. However, any given system tends to stabilize in only a subset of all possible patterns. Stable and recurrent states are called *attractors*, highly "absorbing" states to which the system frequently returns. For example, depression has been described as an attractor; an emotional state from which it is difficult to emerge and that has a high probability of recurrence (Johnson & Nowak, 2002). In contrast to attractors, there are other states that never or rarely occur called *repellors*. An example of repellor in interpersonal dynamics would be mutual positivity (i.e., laughing together) within severely distressed married couples. Hence, a system's state space is configured by both repellors and attractors. These concepts are often represented as an undulating landscape of peaks and valleys (Figure 1). The behavior of the system (series of states) is traceable as a trajectory that moves around the state space (often represented as a marble rolling in and out of attractor basins). The width and depth of an attractor corresponds to the strength of its pull on the trajectory: a strong attractor is deep (attractor A in Figure 1) or has a wide basin (attractor basin C in Figure 1), whereas a smaller and/or more shallow basin has a weaker influence on the behavior of the system (attractor B in Figure 1). Repellor D of the state space in Figure 1 is highly improbable, given that the state space slopes in every direction away from it toward one of the attractors.

This conceptualization of a system's structure and dynamics is a useful way to depict patterns of behavior in *real time*. However, systems also change over time. The way that dynamic systems change is through transformations at a structural level – a reconfiguration of the state space called a *phase transition*. This is change at a deep level, not simply fluctuations or variations in relatively stable real-time patterns. During a phase transition, the size, shape, and/or location of attractors and repellors on the state space may change to create new stable patterns of behavior. This kind of transformation first requires that the old stable configuration breaks down in order to make way for the new one. This transitional period, therefore, is characterized by a temporary increase in the variability of real-time behavior as the system becomes unstable and less predictable. Thus, phase transitions provide a way to understand the relations between real- and developmental-time scales. Several normative developmental transitions have been shown to exhibit properties of a phase transition, including major shifts in walking (Thelen & Ulrich, 1991), infant socio-emotional habits (Lewis, Zimmerman, Hollenstein, & Lamey, 2004), parent–adolescent interactions (Granic, Hollenstein, Dishion, & Patterson, 2003), language (Ruhland & van Geert, 1998), concrete operations (van der Maas & Molenaar, 1992), and infant prehension (Wimmers, Savelsbergh, Beek, & Hopkins, 1998).

[2] A state is a qualitatively distinct condition of a system at a particular moment in time. Thus, states can be represented as values of a variable or set of variables, or as categories. For a developmental scientist, there are many possible states that could be analyzed: behaviors, emotions, attentional foci, etc.

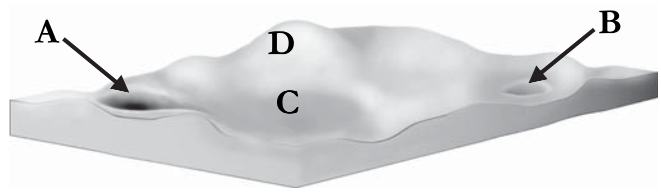

Figure 1. Hypothetical state space configured by three attractors and one repellor. From Martin, Fabes, Hanish, and Hollenstein (2005).

Furthermore, the temporary instability of a phase transition also makes a system more sensitive to perturbations. Thus, external factors have the greatest influence during these periods. This characteristic has two important implications for behavioral development. First, a developmental phase transition may be an exceptionally vulnerable period for a maturing child. The negative influence of peers during the adolescent transition is a good example of this sensitivity. Second, phase transitions may implicate optimal periods for interventions since the system (i.e., child, family) is poised for change. For example, clinical treatment programs such as parent management training to remedy child behavior problems may be most effective during a developmental phase transition than either before or after this period (Granic, 2005; Granic & Patterson, 2006). Both of these implications suggest that identifying the nature and timing of developmental phase transitions is an important research direction. In a subsequent section, I describe several studies that have tested the developmental phase transition hypothesis.

State space, attractors, and phase transitions are useful concepts for understanding developmental processes. These ideas need to be tested empirically. Unfortunately, the common methodologies in the social sciences were developed for the analysis of linear, closed systems, not complex, dynamic, and adaptive systems (Richters, 1997). However, there are mathematically intensive DS methods for exploring system dynamics that include differential equations and simulation models (Gottman, Murray, Swanson, Tyson, & Swanson, 2002; Steenbeek & van Geert, 2005). Indeed these are essential tools for understanding complex developmental processes, yet they remain relatively esoteric and certainly underused in developmental research.[3] Why? There are several possible reasons: (1) typical developmental data simply lack the fine-grained measurement required for the calculation of model parameters; (2) model parameters need to be highly specified and based on theoretical assumptions, but without substantive observations of the dynamics at issue, these assumptions can be pure guesswork and make interpretation difficult; (3) the techniques are simply beyond the purview of most developmentalists because they require conceptual and labor-intensive efforts that are beyond the "zone of proximal research," to paraphrase Vygotsky. That is, rather than making a huge investment in a novel procedure that may not pan out, researchers typically employ a more cautiously pragmatic approach. Thus, a method that could make the technically advanced techniques more accessible to a wider audience as well as inspire non-DS-oriented researchers to explore temporal dynamics would go a long way to advance developmental science. The SSG method is well-suited to fit this niche.

State space grids

Inspired by a DS approach to development, Marc Lewis and colleagues (Lewis, Lamey, & Douglas, 1999) developed the state space grid method to fill the methodological void. The SSG method is a graphical approach that utilizes ordinal data and quantifies these data according to two dimensions that define the state space for the system. As an example, consider a parent–child dyad as a system. With this method, the dyad's behavioral trajectory (i.e., the sequence of behavioral states observed during an interaction) is plotted as it proceeds in real time on a grid representing all possible behavioral combinations. Each cell of the grid represents the simultaneous intersection of each dyad member's behavior. The parent's coded behavior is plotted on the *x*-axis and the child's behavior is plotted on the *y*-axis. Any time there is a change in either person's behavior a new point is plotted in the cell representing that joint behavior and a line is drawn connecting the new point and the previous point. Thus, the grid represents a sequence of dyadic events. For example, a hypothetical trajectory representing 15 seconds of parent–child behavior is presented in Figure 2. The state space is formed by the intersection of an ordinal set of affect categories for both parent and child: High Negative, Low Negative, Neutral, Low Positive, and High Positive. As shown in Figure 2, the size of the plot point corresponds to the duration of each dyadic behavior and the location of the plot point within a cell is random. The sequence depicted begins in the mutually Low Positive cell followed by 3 seconds in the Mother Low Positive/Child Low Negative cell, 4 seconds in the mutually Low Positive cell again, 2 seconds in the Mother Neutral/Child Low Positive cell, 2 seconds in the Mother Neutral/Child High Negative cell, and finally 2 seconds in the mutual High Negative cell.

The image in Figure 2 was created with GridWare 1.1 (Lamey, Hollenstein, Lewis, & Granic, 2004), a free program that can be downloaded from the web (www.statespacegrids.org). Any time series with two or more synchronized streams of categorical data can be used as input. The format required of the data files is a tab-delimited text file for each trajectory that has at least three columns: Time of Onset (or Event Number for event-based data lacking duration information), and one column of sequential data for each axis (i.e., mother behavior and child behavior). Table 1 provides some examples of two-dimensional state spaces. Thus, any researcher interested in the dynamics among two synchronized variables can easily use this technique. In fact, even though the method was developed with DS research in mind, it is not necessary to adopt this approach in order to find it valuable. In general, there are three ways that SSGs are useful: (1) as a visual tool to depict the temporal patterns among two (or more) variables that are synchronized in time, (2) as an exploratory tool for developing hypotheses about processes that unfold in time, and (3) as a source of measures not available with existing methods. Each SSG and the measures derived from it can represent a single trajectory (e.g., a sequence of states for one

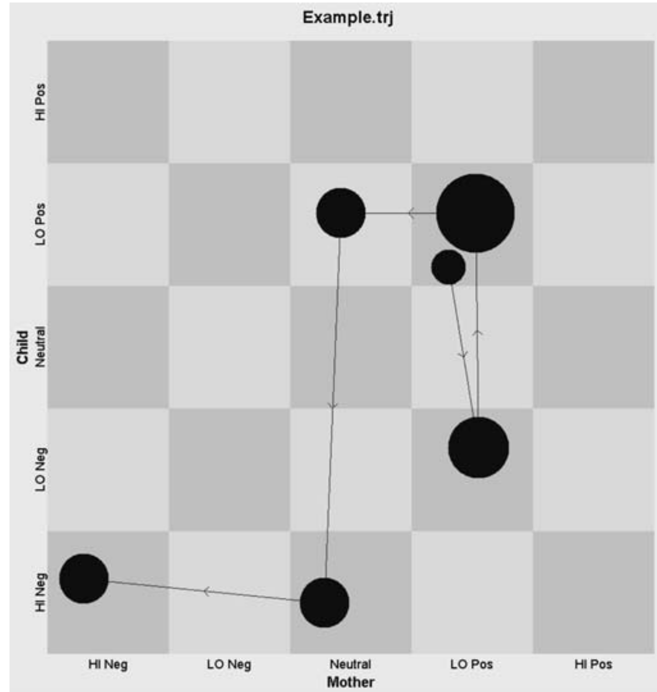

Figure 2. An example state space grid depicting 15 seconds of a parent–child interaction. The size of the plot point denotes the duration of each dyadic event.

parent–child dyad), a selected group of trajectories (e.g., a control group), and/or the entire sample. The remainder of this article is dedicated to describing SSG studies to date and all of the measures described are available with the GridWare program.

Brief review of SSG studies to date

Since the original SSG study (Lewis et al., 1999), there have been eight published empirical reports (Dishion, Nelson, Winter, & Bullock, 2004; Granic et al., 2003; Granic & Lamey, 2002; Hollenstein, Granic, Stoolmiller, & Snyder, 2004; Hollenstein & Lewis, 2006; Lewis, Granic, & Lamm, 2006; Lewis et al., 2004; Martin et al., 2005). What follows is a review of these studies. All of these are studies of developmental phenomoena, yet only some have been longitudinal with explicit analysis of the relations between real- and developmental-time scales. Please note that although "longitudinal" can refer to both real- and developmental-time measures (e.g., moment-by-moment changes in emotions during a 5-minute interaction versus average emotional intensity across monthly measurement occasions), I use the term here to refer solely to studies at a developmental-time scale – those with several measurement occasions separated by a month or more. Because the focus of this article and the special issue is on developmental methods, the cross-sectional (single measurement occasion) studies are reviewed briefly but the longitudinal studies are described in more depth.

Cross-sectional (real-time) studies

Region analyses. One approach to studying recurrent, stable patterns of behavior is to start with an a priori definition of an

[3] Recently, however, Boker and Laurenceau (2006) have made differential equation modeling more accessible through commonly used SEM software.

Table 1
Example axes for two-dimensional state space grids and references for published reports using each

x-Axis	*y-axis*	*Studies*
Person 1 behavior	Person 2 behavior	Dishion et al. (2004); Granic et al. (2003); Granic and Lamey (2002); Hollenstein (2005); Hollenstein et al. (2004); Hollenstein and Lewis (2006); Lewis, Granic, and Lamm (2006)
Distress	Attentional to mom	Lewis et al. (1999)
Attention to mom	Attention to frustrating toy	Lewis et al. (2004)
Target person's affect	Characteristics of interactant(s)	Martin et al. (2005)
Eye gaze: left–right	Eye gaze: up–down	
Emotional valence	Physiological arousal	
Daily events	Daily mood	
Target person's behavior	Events in video/movie	

attractor state and measure the degree to which a system stabilizes in that state. In terms of a SSG, the strength of these attractors can be defined by the duration or frequency of behavior in a cell or group of cells (i.e., a region). Granic and Lamey (2002) used this approach to study differences in parent–child behavior in sub-types of aggressive children. A prevalent distinction in the developmental psychopathology literature is between aggressive children who are considered "pure" externalizers (EXT), who mostly suffer from an inability to inhibit their impulsive behavior, and children who also have problems with anxiety or depression (MIXED). Granic and Lamey (2002) observed the parent–child interactions in these two groups using a clever DS-inspired design: instead of passive observation, system dynamics were evoked by means of a perturbation. Following 4 minutes of discussion about a frequent conflict at home, the parent–child system was "perturbed" by the instruction to "wrap up, resolve the conflict for good, and end on friendly terms" within 2 minutes. Before the perturbation, there were no differences in the patterns of interaction between the EXT (Figure 3A) and MIXED (Figure 3C) groups. Following the perturbation, however, the EXT group remained in the "permissive" region of the state space, wherein the child was being hostile or negative and the parent was being neutral or positive (Figure 3B, top right). Children in the MIXED group were also hostile or negative following the perturbation, but unlike the pure externalizers, their parents were negative and hostile as well (Figure 3D, bottom left). This study highlighted the usefulness of the SSG method by providing a stark demonstration of behavioral differences between these subtypes with important implications for the kind of interventions that may be appropriate for each group.

Whole-grid analyses. Some of the most innovative SSG studies involve the analyses of the structure or patterns of behavior across the whole state space in contrast to the specific

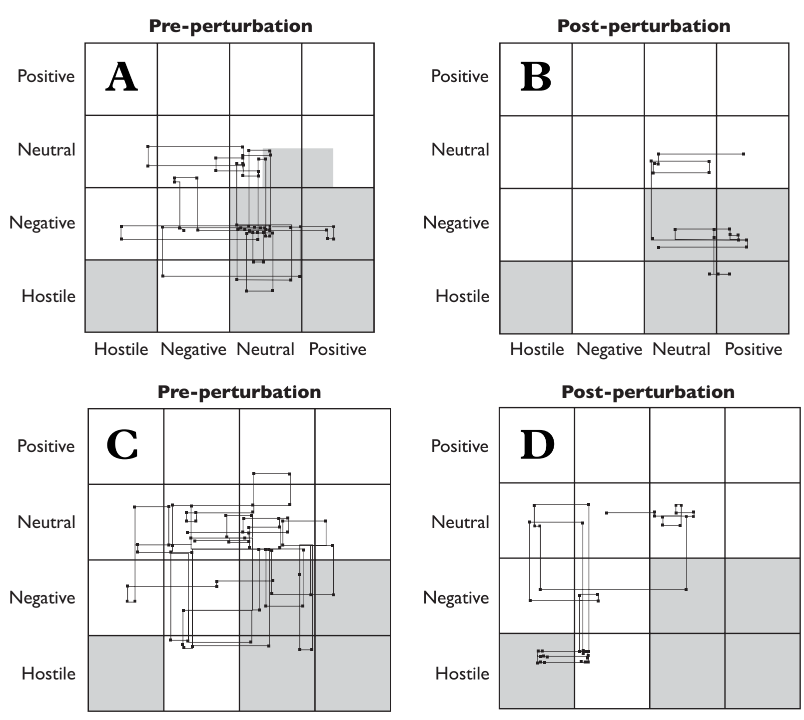

Figure 3. Example SSGs of two mother–child dyads from Granic and Lamey (2002). Parent behavior is plotted on the *x*-axis, child behavior on the *y*-axis. The child in the dyad on the top row was in the EXT group and the child in the dyad on the bottom row was in the MIXED group. The left column shows the pre-perturbation SSG (A and C), and the right column shows the post-perturbation SSG (B and D).

content, as in region analyses. From a DS perspective, the variability of a system is a signal that provides information – not just noise to be minimized (Thelen & Ulrich, 1991). Several SSG studies have used measures of the variability of parent–child and peer interactions to examine the relations between emotion, flexibility and the development of problem behaviors (Dishion et al., 2004; Granic, O'Hara, Pepler, & Lewis, in press; Hollenstein et al., 2004; Hollenstein & Lewis, 2006; Lewis et al., 2006). Flexibility – the ability to adapt to changes in the environment – is an important feature of social interactions and can be operationalized in at least three ways that correspond to SSG measures: (1) the range or number of different behavioral states – a count of cells occupied or dispersion across the grid, (2) the number of transitions between those states – trajectory lines on the grid, and (3) the tendency to perseverate or get "stuck" in a small number of states – the average of all the individual cell mean durations. In Figure 4, for example, the SSG on the left shows a wider dispersion, more transitions (more lines), and lower mean durations (smaller plot points) than the relatively less flexible dyad depicted on the SSG on the right.

Three studies have involved the examination of the flexibility of parent–child interactions. In the first, lower flexibility (i.e., rigidity) in parent–child interactions at the beginning of kindergarten was associated with growth in antisocial and aggressive behavior across kindergarten through the end of first grade (Hollenstein et al., 2004). The second study examined the interactions of mothers and children in a treatment program for aggressive behavior (Granic et al., in press). Those who dropped below clinical levels of aggression following treatment were more flexible than those who retained their clinical diagnosis despite the intervention. Finally, a recent study explicitly examined whether negative emotions could account for a decrease in flexibility during conflict relative to nonconflict situations (Hollenstein & Lewis, 2006). Indeed, the expression of negative emotion during mother–daughter conflict in early adolescence corresponded with reduced flexibility.

A second way that the overall patterns of behavior depicted on SSGs have been analyzed is with a measure of organization or predictability: entropy. Using the concept of entropy from information theory (Shannon & Weaver, 1949), Dishion and colleagues (2004) investigated the organization of peer interactions among antisocial and normal boys. Based on the logged conditional probabilities of verbal behavior between two adolescent boys, low entropy indicated a highly organized pattern, whereas high entropy indicated a relatively unpredictable pattern. Adolescent boys who engaged in low entropy deviant talk (i.e., breaking rules and norms) were the most likely to continue antisocial behavior into adulthood.

One of the most exciting set of results to date comes from a study of brain–behavior relations in a sample of children referred to clinics for aggressive behavior in school (Lewis et al., 2006). Children's brainwave patterns were measured by electroencephalogram (EEG) during a go/no-go task before, during, and after a negative mood state was induced. In the B-block of trials, the children lost all points gained in the A-block of trials. The C-block trials (a repeat of the A-block) were of primary interest to see how the children reacted to the loss of points by the end of the B-block (by the end of the C-block, however, they regained their points to earn a prize). The children's ability to inhibit their prepotent response ('going' on a no-go trial) was measured by a well-established brain wave component – the "inhibitory N2." High amplitude N2 waves indicate more active inhibition or effortful attention (Lewis, Lamm, Segalowitz, Stieben, & Zelazo, 2006). This N2 amplitude was positively correlated with each of the three measures of flexibility measured a few hours later during a conflict interaction between the child and mother (average r = .35). Moreover, these measures of flexibility accounted for 17–24%

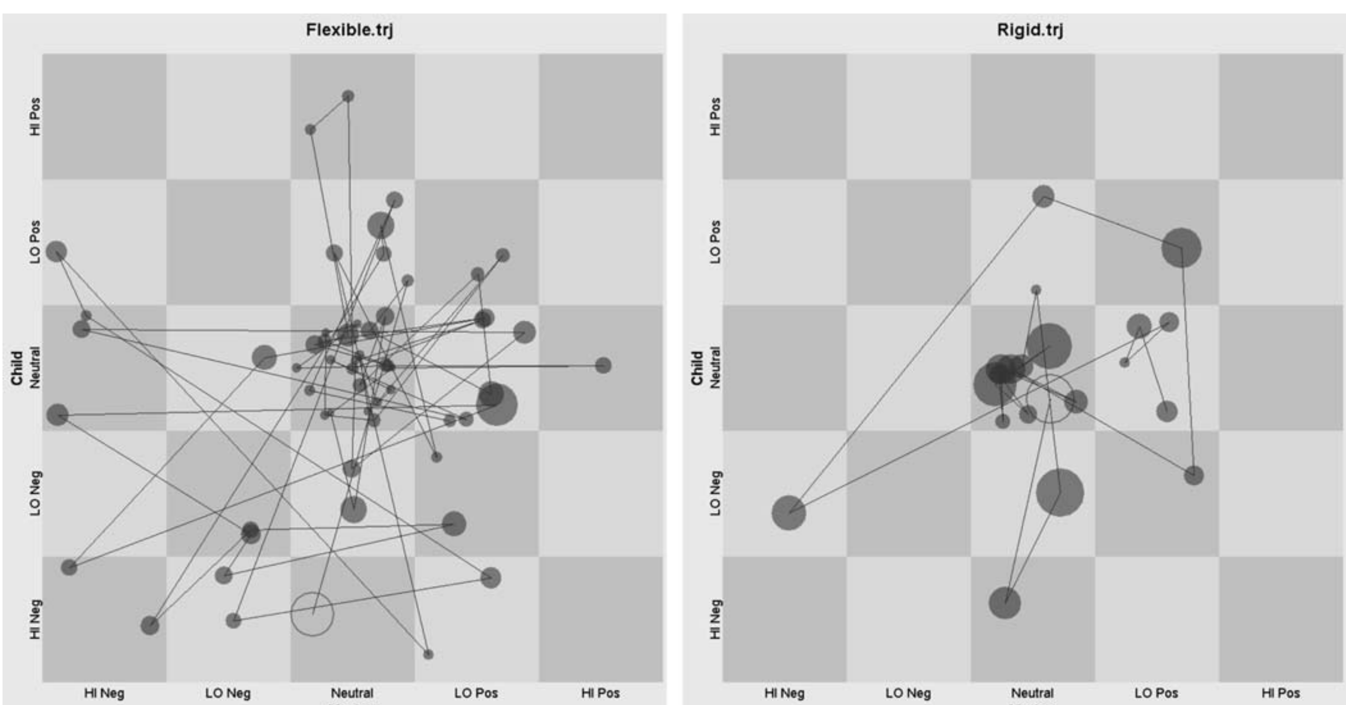

Figure 4. Examples of a relatively flexible mother–child interaction (left) and a relatively rigid one (right). Mother behavior is plotted on the x-axis and child behavior on the y-axis.

of the N2 amplitude variance even after controlling for variations of the EEG task (number of usable trials, etc.) and the amount of negative emotion expressed during the conflict discussion. Thus, these SSG measures of interpersonal flexibility appear to be associated with the ability to inhibit behavioral responses. These preliminary results have far-reaching implications for the understanding of emotion regulation processes in children and families related to the development of problem behaviors and psychopathology.

Taken together, these studies demonstrate novel methods for measuring what clinicians and other researchers have identified in theoretical writing for years: problematic or pathological behavior is characterized by rigid or inflexible behavior patterns. Most importantly, it was the structural patterns of behavior (i.e., flexibility, entropy) in these studies that were predictive above and beyond the content (i.e., total negative emotion, talk about deviant behavior).

Group analyses. The studies reviewed so far have relied on observations of an individual or a dyad. Many developmental psychopathologists, however, are interested in how group social processes affect problematic behavior. Martin et al. (2005) adapted SSG analyses for the study of peer interactions on a pre-school playground. Each (target) child on the playground was observed many times throughout the school year to obtain several measures of their interactions. Each measure corresponded to one of four possible dimensions on an SSG: gender of target child, gender of peer, behavioral tendencies of the target child (competent, externalizing, or internalizing), and behavioral tendencies of the peer. Each interaction "event" on the playground was coded in each of these categories. Analyses revealed an increase in sex-segregated behavior over the course of the year (boys played with boys, girls played with girls). Although not reported in Martin et al. (2005), another way to display these data is shown in Figure 5. Rather than depict the behavior of one child with peers, this SSG is a summary of all the children in the study. In Figure 5, the data are collapsed to two dimensions, one corresponding to the characteristics of the target child and the other to the characteristics of the peer(s) with whom the child was interacting. The nodes represent the number of observed interaction events between children. From this image it is apparent that the competent girls tended to play with each other the most, but also interacted some with each of the other gender/behavior combinations. In contrast, internalizing boys appeared to have the least interaction with anyone. Thus, SSGs can also be used to display information about the distribution of values in a matrix.

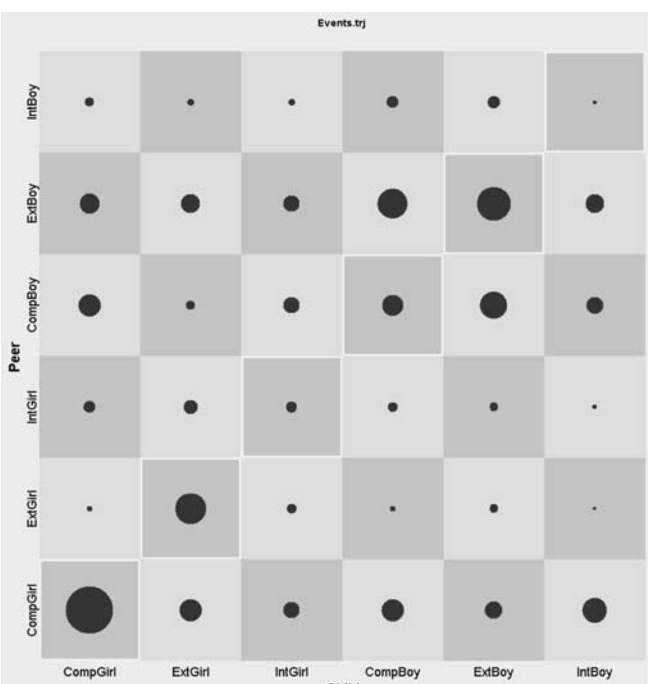

Figure 5. An example of using an SSG to display the distribution of values in a matrix. The gender and behavioral grouping are combined to make six categories for the target child (x-axis) and peer (y-axis): Competent Girl, Externalizing Girl, Internalizing Girl, Competent Boy, Externalizing Boy, and Internalizing Boy.

Longitudinal (real- and developmental-time) studies

Attractor analyses. As described above, the state space of a system is configured by attractors – absorbing states that have a much higher probability of recurrence than other states. At a simplistic level, these states may be identified in synchronized time series with measures of frequency or duration. For example, dysfunctional parent–child interactions may be identified by excessively frequent bouts of mutually hostile behavior. A successful therapeutic intervention, therefore, could be measured by the absence of or decrease in the strength of that mutual hostility attractor (Granic & Patterson, 2006). However, in the original work on SSG analysis, Lewis et al. (1999) describe more thorough methods for: (1) identifying an attractor, (2) measuring an attractor's strength, and (3) testing for the stability of that attractor over time. This analytical approach is more precise than that of the Granic and Lamey (2002) study and, although attractor analysis can be conducted within nonlongitudinal designs, the Lewis et al. (1999) study investigated the stability of real-time attractors over developmental time.

The state space in the Lewis et al. (1999) study was based on observations of infants at 2 and 6 months of age during brief, distressing tasks. The SSG axes were ordinal categories of the intensity of distress and the infant's attention to mother (angle of gaze). The study investigated how early individual differences in emotion-related behavior cohere and stabilize within the first 6 months. Attractors on this state space were identified through a *winnowing* procedure – an iterative procedure using the total duration in each of the occupied cells. Expected values were calculated from the total duration divided by the number of cells (as used in chi-square calculations) and the sum of squared deviations (observed minus expected, squared) was divided by the number of cells in the analysis to obtain a heterogeneity score. Cells were eliminated one by one, starting with those with the lowest total duration, until there was little change (<50%) in the heterogeneity score. This resulted in one or two cells that were relatively homogenous with high total durations for each observation session.

Once the attractors were identified, a second set of analyses measured the strength of these attractors. First, influence was calculated from the expected values of transitions (changes from each cell into the attractor) and subjected to chi-square analyses to determine if the number of transitions into the attractor exceeded chance expectations. Second, the return time to the attractor was calculated as the average number of seconds between visits to the attractor cell. Thus, smaller return time values indicated a more stable attractor – the infant had difficulty staying away from that state. Return time values were subjected to another test against chance and then used as an index of stability.

Finally, attractors were compared within infants across observation sessions (Figure 6). Between the ages of 2 and 6 months, the infants' behavior became less variable and attractor strength increased. Importantly, several strong correlations (.7 to .8) between attractor strength (influence and stability) at 2 months and 6 months were reported. Among these were negative correlations between attractor influence at 2 months and stability (return time) at 6 months, and between stability (return time) at 2 months and attractor duration at 6 months. These relations held or improved after controlling for the specific location of attractors on the state space grid. Thus, the relative strength of early habits predicted the strength of these habits 4 months later.

These attractor analyses illustrate how patterns of behavior form and become stable over time and could be used in a number of developmental research settings. Normative developmental acquisitions (e.g., walking, theory of mind, formal operational thought) can be examined as attractors that form and stabilize with experience (Thelen & Ulrich, 1991). In terms of developmental psychopathology, some attractors may be considered adaptive and healthy, whereas others may indicate dysfunctional patterns. Clinicians using this technique could use attractor analysis to identify these problematic attractors as part of a diagnostic assessment and then, over the course of treatment, measure the dissolution of that attractor in lieu of other, less problematic ones. Indeed, mental health issues including depression (Johnson & Nowak, 2002), antisocial behavior (Granic & Dishion, 2003), and post-traumatic stress disorder (Tryon, 1999) have been examined in terms of attractors. Certainly, this attractor concept can be applied to better understand many disorders, such as behavior patterns in obsessive–compulsive disorder, thought patterns in schizophrenia, and eating patterns in the development of bulimia and anorexia.

Developmental phase transitions. The Lewis et al. (1999) study documented the emergence of a stable socioemotional pattern in infancy. However, as discussed earlier, development is punctuated by major structural shifts called phase transitions during which these patterns are reorganized into new forms. In terms of SSG analysis, the relation between real-time patterns and a developmental phase transition across four measurement occasions is depicted in the diagram in Figure 7. As indicated by this diagram, there are actually two ways that the characteristic variability of a phase transition may be observed. First, the real-time patterns *within* each measurement occasion become more variable during the phase transition before settling down to a new stable pattern afterwards. Second, there may also be a lack of consistency *across* measurement occasions provided that they are spaced relatively close in time. Studies that tested the developmental phase transition hypothesis by examining each of these two types of variability are described next.

Following the relatively stable period of mid to late childhood, the changes of early adolescence are relatively brief and not typically associated with long-term adjustment problems

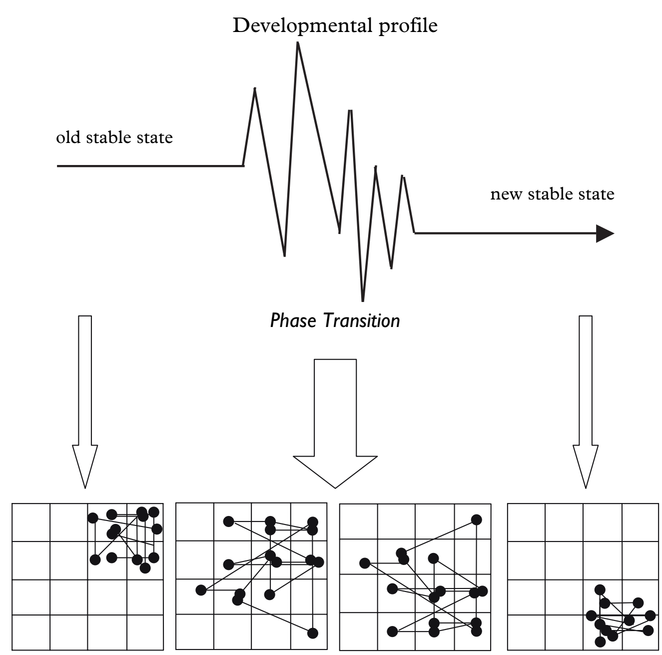

Figure 7. Schematic diagram of the relationship between real-time variability and a phase transition in developmental time.

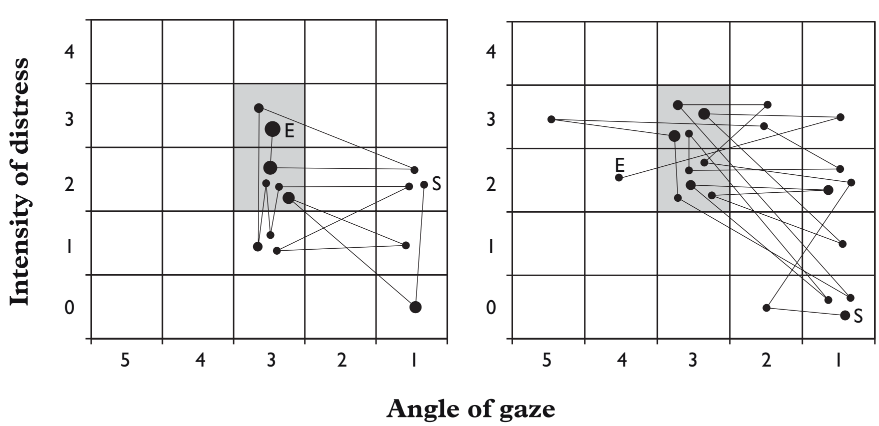

Figure 6. Two sessions for one infant at 2 and 6 months of age. Distress (*y*-axis) was an ordinal index (0–4) and the angle of gaze (*x*-axis) ranged from 1 (looking directly at mother) to 5 (complete gaze aversion). Attractor consistency, rapid return time, and moderate influence are evident in both. From Lewis et al. (1999).

(Graber & Brooks-Gunn, 1996; Steinberg, 2001). However, emotion-related behavior during this period is consistent with characteristics of a developmental phase transition: a peak in variability and sensitivity to perturbations. Adolescence has frequently been described with words like "re-organization," "realignment," "redefinition," "disequillibration," and "flux" (Cicchetti & Rogosh, 2002; Collins, 1990; Larson, Moneta, Richards, & Wilson, 2002; Paikoff & Brooks-Gunn, 1991; Steinberg, 1990). The transitioning adolescent suddenly experiences new ways of thinking (Keating, 2004), a new body (Paikoff & Brooks-Gunn, 1991; Susman & Rogol, 2004), different sleep patterns (Carskadon, Vieira, & Acebo, 1993), more negative emotions, increased emotional sensitivity, reactivity, intensity, and lability (Larson et al., 2002; Rosenblum & Lewis, 2003), diminished experience of rewards (Spear, 2000), higher expectations (Eccles, 2004), more stressful events (Brooks-Gunn, 1991), greater sensitivity to stress (Larson & Ham, 1993), greater risk for psychopathology (Farrington, 2004; Graber, 2004), more peer influence (Brown, 2004), and neither the regulatory capacities nor the coping skills to compensate for this barrage of novelty. Under these conditions, it would be quite functional and adaptive for variability to peak in early adolescence.

Two studies were conducted that directly tested the adolescent developmental phase transition hypothesis using SSGs. The first was a five-wave longitudinal study on parent–boy interactions that began when the boys were 9–10 years old and continued until the boys were 17–18 (Granic et al., 2003). Parents and sons were observed during two 10-minute discussions about self-identified conflicts at home. Codes of the conversational content and valence for each participant were collapsed into four categories (Hostile, Negative, Neutral, and Positive) to create 4 × 4 SSGs. Two measures of dyadic variability were used: Cells (the number of unique cells visited) and Transitions (the number of changes among those cells). These measures were used in repeated-measures ANOVAs with polynomial contrasts. Consistent with the developmental phase transition hypothesis, these two measures peaked when the boys were just entering adolescence at age 13–14 (Figure 8). However, because of the way that the SSGs were constructed, it was possible that the reason for this peak in flexibility was due to an increase in conflict. That is, the increase in Cells and Transitions could be due to an increase in behavior categorized as either Negative or Hostile. To account for this possibility, conflict was measured by the number of visits to the mutual negativity region of the grid (the four cells that combined the Negative and Hostile categories for both parent and child). Conflict increased from ages 11–12 to 13–14 in the same way as Cells and Transitions. However, unlike the immediate decrease in variability after age 13–14, conflict continued to increase at ages 15–16 before finally dropping off in late adolescence. Thus, during the transition parents and sons were both more conflictual and less stable in their behavior, yet their patterns of conflict became more stable after the transition. These results were consistent with findings that conflict frequency peaks in early adolescence but the intensity of the negative affect during those conflicts peaks later in mid-adolescence (Laursen, Coy, & Collins, 1998).

Following the success of this first study of the adolescent phase transition, a second study was conducted that examined mother–daughter conflict discussions to see if the same changes in variability would occur across the female transition into adolescence (Hollenstein, 2005). These are unpublished dissertation data; therefore what follows is a bit more detailed than what has been reviewed so far. In order to capture the most tumultuous period for girls, the mother–daughter dyads were observed across four measurement occasions that traversed the girls' switch into a new middle school in grade 7. Not only does this school transition coincide with the average age of mid-puberty (i.e., menarche; Susman & Rogol, 2004), but it has also been associated with many adjustment difficulties (Eccles, 2004), especially if combined with several stressful life events (Simmons & Blyth, 1987). Thus, the developmental phase transition profile of mother–daughter variability from grades 6 to 8 was tested for a quadratic peak in grade 7. Moreover, the number of stressful events that occurred about the same time as the school change was used to create Low Stress (less than three stressful events) and High Stress (more than three stressful events) groups based on critical thresholds found in previous research (Simmons, Burgeson, Carlton-Ford, & Blyth, 1987).

Rather than collapse code categories to make a smaller state space, the mother–daughter study was based on the raw code categories to make a 10 × 10 SSG (Figure 9). Mothers' and daughters' affect during a discussion of a self-identified upsetting conflict was coded with the Specific Affect 10-code system (Gottman, McCoy, Coan, & Collier, 1996). Variability was measured by the number of Transitions and by Dispersion, or spread of behavior across cells: the sum of the squared proportional durations across all cells, corrected for the number of cells, and inverted so that values range from 0 (no dispersion at all – all behavior in one cell) to 1 (maximum dispersion –

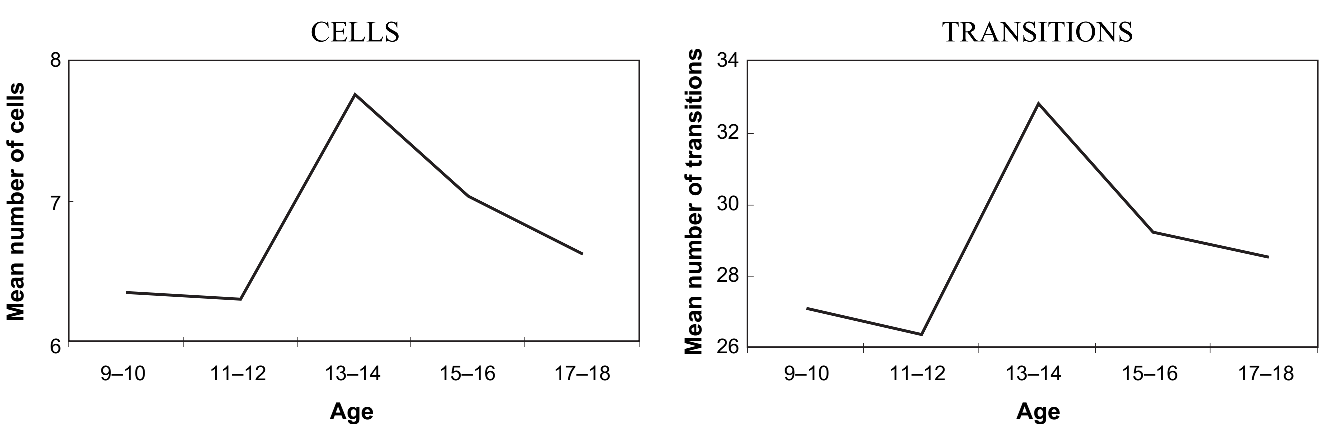

Figure 8. Longitudinal profiles of SSG measures Cells and Transitions across five waves of parent–boy interactions. From Granic et al. (2003).

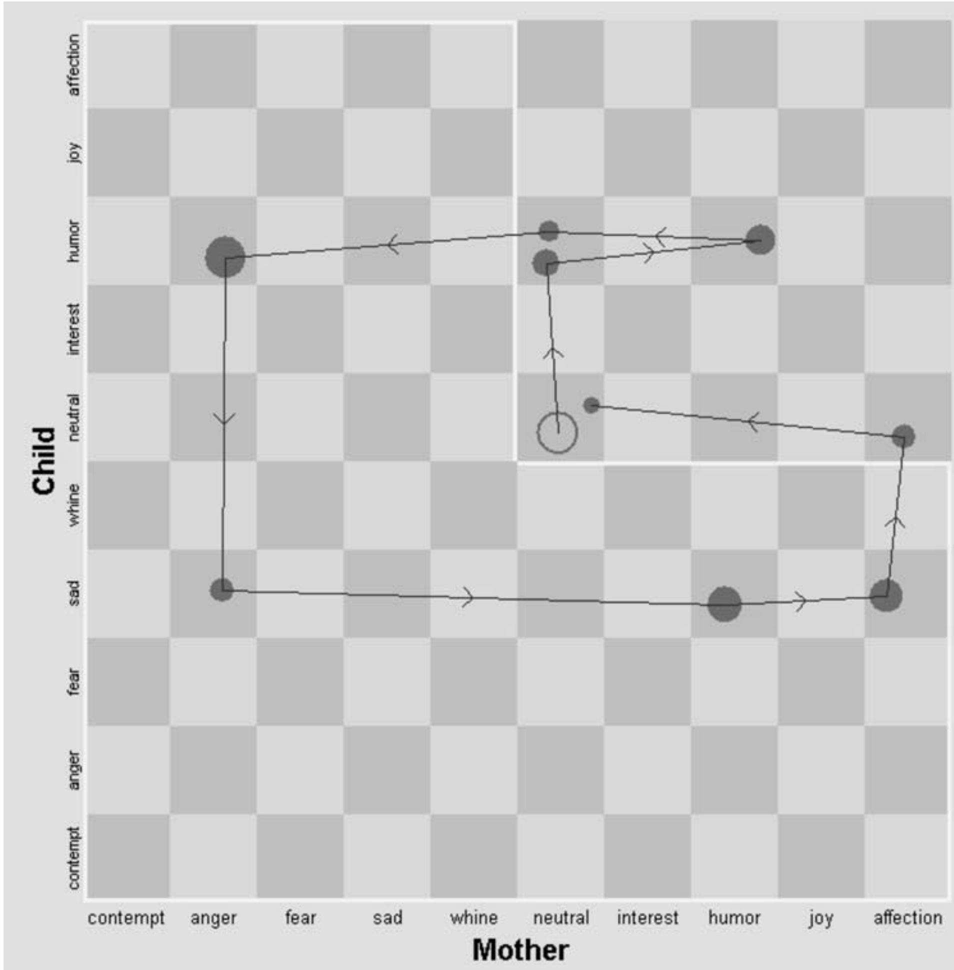

Figure 9. State space grid used for the mother–daughter adolescent phase transition study. The duration in negative emotional states was measured as the amount of time in the highlighted L-shaped region.

behavior equally distributed across the grid). This measure is created by the formula:

$$1 - [[(n\Sigma(d_i/D)^2) - 1]/n - 1]$$

where D is the total duration, d_i is the duration in cell i and n is the total number of cells in the grid. This measure has the advantage over the raw count of the number of cells visited by controlling for the proportional durations in cells (i.e., a brief, unique visit to one cell has less influence).

Unlike the adolescent boys' study and contrary to predictions, there was no change in mother–daughter variability across the school transition period. However, individual differences in the amount of stress at the transition appeared to account for this effect. As shown in Figure 10, there was a significant divergence of the Low Stress and High Stress groups right at the beginning of grade 7. Once the highly stressed girls were removed, the unstressed girls showed the characteristic profile of a phase transition – both Transitions and Dispersion peaked in grade 7 as hypothesized. Why would stress reverse the phase transition effect? One possibility is that members of the High Stress group were also more emotionally negative and this increase in negative emotion would thus make the dyads more rigid and less variable. To test this possibility, **N**egative Emotion was measured as the total duration within the L-shaped portion of the grid pertaining to dyadic states in which one or both participants were expressing negative emotions (Figure 9). However, as also shown in Figure 10, there were no differences in Negative Emotion between the two groups across waves. In fact, both groups became increasingly more negative over time, replicating a well-established pattern of parent–adolescent conflict in which the intensity does not peak until middle adolescence (Laursen et al., 1996). A second possibility to explain the divergent patterns of variability is that, in the presence of stress during the early stage of the transition, dyads may be reluctant to engage in interactions that will add to this stress. In essence, they may be resisting normative developmental changes or at least reacting more cautiously than those who are not stressed. Although speculative, it is possible that these dyads were relying heavily on old methods of coping and self-regulation and were therefore less likely to try out new strategies.

These two adolescent studies show how the SSG method can be used to test DS-inspired hypotheses and holds promise for future research on adolescent emotional behavior. Characteristic system dynamics were measured with relatively simple indices yet provided novel predictions and unique insight into developmental processes. Similarly, the final study in this

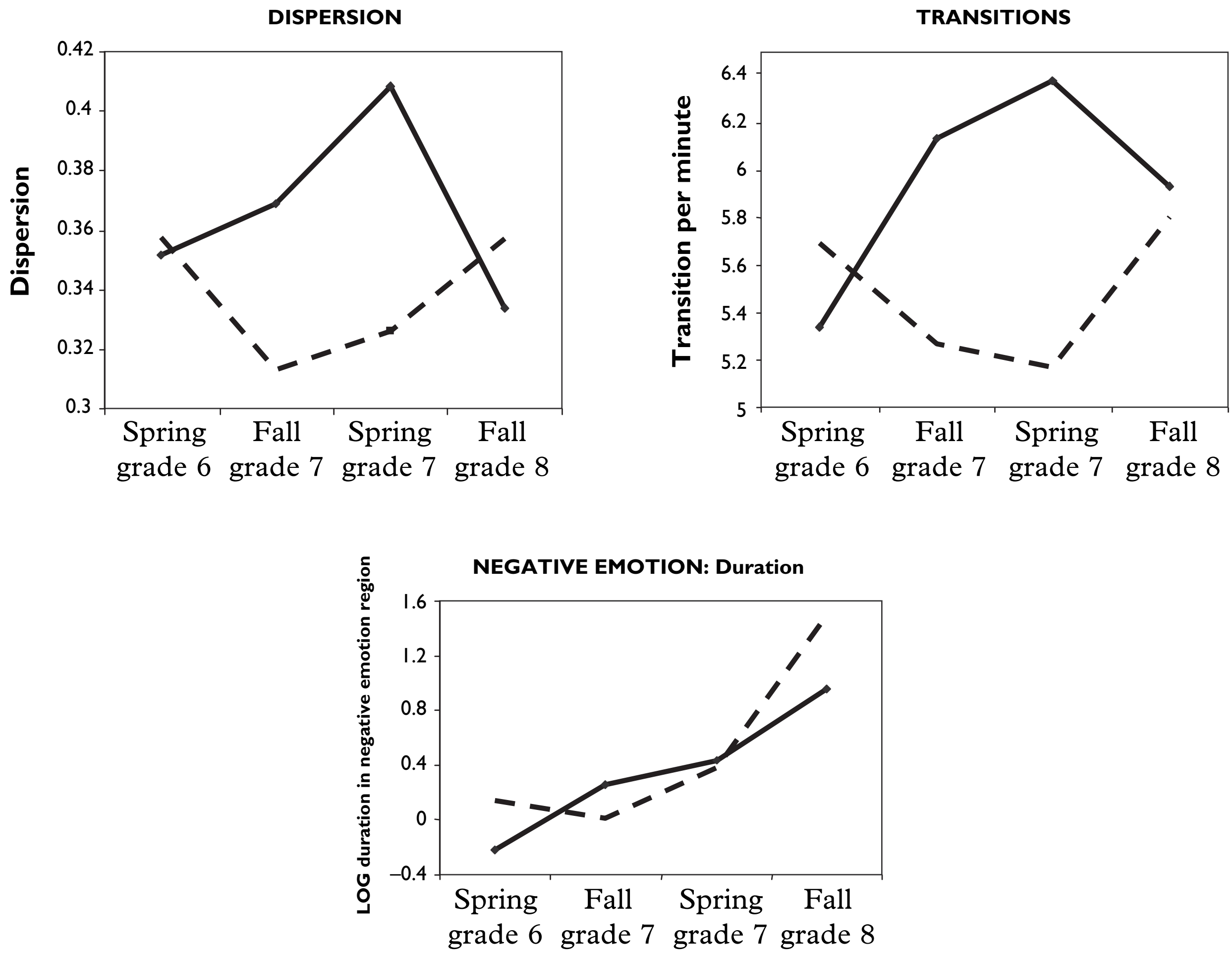

Figure 10. Results from the mother–daughter adolescent phase transition study. The Low Stress group is plotted as a solid line and the High Stress group is plotted as a dashed line.

review employed two novel measurement techniques to test for a developmental phase transition in toddlerhood.

Near the end of the second year (approximately 18–21 months), children go through a number of social, cognitive, and emotional shifts. Changes during this period include an awareness of the other's intentions (Tomasello, 1995), possessiveness (Lewis & Michalson, 1983), a sense of self (Kagan, 1998), shyness or embarrassment (Lewis, Sullivan, Stanger, & Weiss, 1989), empathy or prosocial behavior (Eisenberg, 1992; Zahn-Waxler & Radke-Yarrow, 1982), negativism (Dunn, 1988), and a peak in tantrums (Kopp, 1992). As with adolescence, this collection of concomitant changes has led some researchers to examine this period as a developmental phase transition. Lewis et al. (2004) observed the socioemotional habits of 24 infants once a month from 14 to 25 months of age during a distressing task. Infants were given a frustrating toy (an interesting toy enclosed in a see-through box or a broken Jack-in-the-Box) while their mothers sat reading a magazine several feet behind. Attention is perhaps the most rudimentary form of self-regulation in the face of distress, thus SSGs were created for each observation with five levels of infant attention to the mother on one axis and five levels of infant attention to the toy on the other. The developmental phase transition hypothesis was tested by analyzing month-to-month change in attentional habits using two novel measures: cluster change and inter-grid distance scores.

For each task, the individual cell durations for each SSG for every child at every month were entered into a k-means cluster analysis. Thus, 25 variables, one for each *x*-axis/*y*-axis combination (i.e., cell), were entered into the analysis. Each SSG was classified into one of five clusters so that each infant received a cluster membership for each month. If cluster membership changed from one month to the next, the infant received a score of 1 for that month. If the cluster membership did not change, the infant received a score of 0. Hence, across the 12 months of observation, each infant was assigned 11 cluster change scores for the enclosed toy task and 11 scores for the jack-in-the-box task. As hypothesized, infants showed the greatest month-to-month change (highest mean cluster change scores) between 18–21 months for both tasks. That is, their attentional habits were the least stable during this transitional period.

A second way that this monthly difference between SSGs was analyzed was with the inter-grid distance score (IDS). As shown in Figure 11, each cell's duration from one month was subtracted from the same cell's duration in the previous month. These differences were then squared and summed across cells as in a Euclidian distance algorithm. Thus, as with the Cluster Change Score, there were 11 IDS scores for each infant for each task. As predicted, IDS peaked within the 18–21-month window for both tasks.

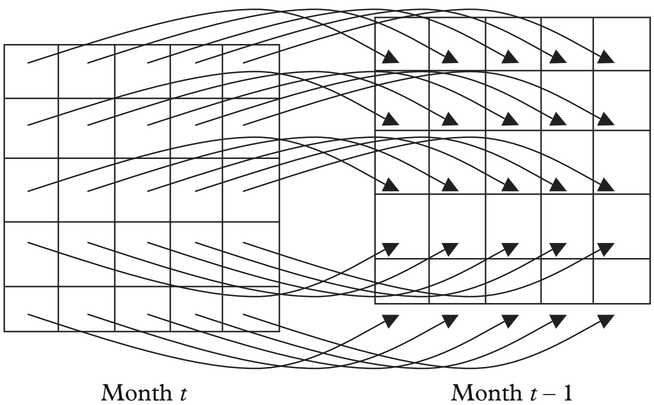

Figure 11. Diagram of the calculation of the Inter-grid Distance Score: Duration in each cell for Month t is subtracted from the corresponding cell duration for Month t – 1; these differences are then squared and summed across all 25 cells.

Considerations for using SSGs

There are two main issues to consider before using the SSG method: the parameters of the state space and the appropriateness of the data. As defined above, the state space is the space of all possible states of the system. The first thing to consider is "What is the system?". In the examples described above, the system has been defined as the individual, the dyad, or a small group. In reality, this identification of the system pertains to the scope or level of analysis chosen by the researcher rather than any absolute identification. I began with a description of hierarchical organization and this may be a helpful heuristic with which to decide the appropriate level of analysis. For example, the system of interest is a middle level of organization made up of micro elements and nested within a more macro organization. Hence, the dyadic system is comprised of the moment-by-moment dynamics and nested within larger social structures (i.e., family) or simply nested within longer stretches of time (i.e., childhood through adolescence). Thus, the definition of the system is a matter of choice. However, the construction of the state space is another matter that may constrain the options.

Pragmatically, a state space can simply be defined via the intersection of two dimensions of importance. Thus far, only two-dimensional SSGs have been discussed, but certainly this space can be constructed from many dimensions. For simplicity, I focus on two-dimensional state space to provide guidelines for interested researchers. The most significant constraint on the choice of dimensions is that the subcategories within each dimension must be mutually exclusive and exhaustive. Failure to satisfy this constraint renders the SSG technique unusable. A few other suggestions about the choice of state space dimensions include: (1) both ordinal and nominal categories are acceptable. However, ordinal categories may be optimal for interpretation of the measures because adjacency has some meaning. As can be seen from many of the examples presented here, a quasi-ordinal arrangement of nominal categories (i.e., affect) is a reasonable compromise; (2) it best if there is some variability across the categories. If the vast majority of events occur in one category, then it might be better to reconsider the use of that dimension to analyze the system dynamics; (3) although only two dimensions may be visible at any one time, it is possible to have more than two dimensions in the GridWare program; (4) the really unique information offered by SSGs is that the intersection of two categories in time is the unit of analysis. This is often a stumbling block for new users who are used to thinking in one dimension. Thus, it may be helpful to consider what micro units (i.e., cells) would be of interest.

You can use SSGs to explore or analyze your data if your data meet the following conditions: one (preferably two) or more sequences of ordinal or categorical events that are mutually exclusive and exhaustive. Figure 12 is a flow chart for determining the appropriateness of data for SSGs. Each dimension of the state space is defined by a *state variable* that has two or more levels (i.e., low, medium, high Intensity or ordinal levels of Distress). The first question that should be answered is whether or not you have two (or more) state variables. Even with only one appropriate state variable (a sequence of mutually exclusive and exhaustive events), SSGs can be used to create a "lagged phase plot" (or lag plot or reconstructed phase space) in which one axis is the sequence of events at time t and the other axis is the same sequence at time $t + 1$ (Heath, 2000). Thus, each event in the sequence is plotted twice – once as an antecedent and once as a consequence. Of course, the lag can be more than one unit if the researcher so chooses.

Given two or more state variables, the next question is whether each state variable is recorded continuously in time (duration based) or is a sequence of events without information about the duration of each event (event based). The latter is a special case of the former and it is important for the researcher to understand the limits and advantages of each. In general, a duration-based format is preferable because of the greater amount of information. It should also be noted that SSG-appropriate data can have been measured at any time scale. Thus, the intervals between events can be milliseconds or years.

The next question is whether there are gaps in the sequence. If so, can these be identified as missing data? If the data are not a continuous sequence, there is one possibility that may still allow for SSGs. If the data are in an alternating sequence (i.e., conversational turns), then the X/Y paired events can be plotted like a lagged phase plot with X at time t (antecedent) and Y at time $t + 1$ (consequence). Without this alternation, discontinuous sequences cannot be used with SSGs.

The final determination is whether the two streams of events

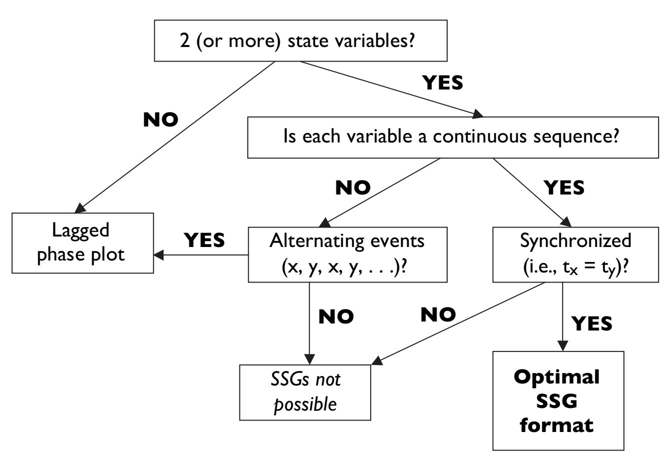

Figure 12. Flow chart for determining the appropriateness of data for SSGs.

are synchronized in time. There are two possibilities: duration-based (the sequence of events is accompanied by information about the duration of each event) and event-based (events occur in sequence but duration is not recorded) data. In either case, the events must be synchronized. For event-based data, this means that each change in state variable X corresponds with a state of Y, although Y may or may not have changed. For example, suppose the state variables were Person 1 and Person 2 and there were three possible states for each: Positive Talk, Negative Talk, and Not Talking – a 3×3 SSG. Further suppose that the first three events in the sequence were Person 1 switching from Positive Talk to Negative Talk to Positive Talk. In order to be usable on a SSG, Person 2 would have to have three events as well, all of them Not Talking. Without that link between state variables, the exhaustive criterion is violated and SSGs are not usable. Event-based data are fairly common and can sometimes be retrofitted into compliance with the SSG criteria. In the example above, perhaps the researcher did not code for Not Talking originally. It is still possible to assume that any time either person was not coded as Positive Talk or Negative Talk that he or she was Not Talking. Other instances of event-based data include measures that are obtained at approximate intervals (i.e., daily diaries).

The ultimate data format is to have complete information about each state variable in time. That is, to have the onset time for each change in each state variable. The offset of each event is also necessary, but in a truly exhaustive categorization scheme, the onset of the next event is the offset of the previous event. Thus, with this arrangement all of the event information is retained but with the added information about the duration of each event. This is the data arrangement that is most amenable to DS analyses.

Future directions

The SSG technique is still relatively new and there are many areas still left to explore. As argued in the opening of this article, the SSG method is a middle road between mathematically intensive and more traditional, static techniques. With regard to the former, SSGs can be used as a visualization tool to display the results of simulations or the coupled time series being analyzed with other methods. For example, Markov models are used to analyze multivariate event sequences. Although GridWare does not yet run such analyses from within the program, the SSGs can be used to display output from these modeling procedures. Coupled differential equations are another example. Output values from one step in the model are iteratively returned as input for the next step and these sequences could be displayed on a grid to enhance understanding and interpretation.

There are several variations of the SSG method not covered in this review because they are still in progress or have yet to be attempted (see Table 1). One of the major innovations being developed is to accommodate both categorical and continuous data. For example, several current projects involve the collection of heart rate and skin conductance during a parent–child interaction. In the grid format, these data are being analyzed by breaking up the continuous heart rate time series, for example, into categories of acceleration, deceleration, and stability for both parent and child. This is interesting and informative but information is lost. Thus, the next version of the GridWare software will allow for both categorical and continuous dimensions. Other variations include: (1) using the state space as a literal map of physical space as in eye tracking (up–down versus right–left dimensions) or in tracking children's location within a classroom; (2) using other units of time such as days as in diary studies of daily events and moods; (3) having one dimension correspond to a dynamic stimulus, such as a video, and the other dimension correspond to an individual's response to events on the video.

In conclusion, I have reviewed the SSG studies to date and highlighted some of the features of the technique that have been reported. Thus far, we have only scratched the surface of possibilities. The SSG method offers an incremental move toward a more complex, dynamic understanding of the processes of development. It is by no means the only such tool in the developmental toolbox, but it certainly will be instrumental in guiding the next phase of research in the early twenty-first century.

References

Bergman, L.R., & Magnusson, D. (1997). A person oriented approach in research on developmental psychopathology. *Development and Psychopathology*, *9*, 291–319.

Boker, S.M., & Laurenceau, J. (2006). Dynamical systems modeling: An application to the regulation of intimacy and disclosure in marriage. In T.A. Walls & J.L. Schafer (Eds.), *Models for intensive longitudinal data* (pp. 195–218). New York: Oxford.

Bronfenbrenner, U. (1979). *The ecology of human development: Experiments by nature and design*. Cambridge, MA: Harvard University Press.

Brooks-Gunn, J. (1991). How stressful is the transition to adolescence for girls? In M.E. Colten & S. Gore (Eds.), *Adolescent stress: Causes and consequences* (pp. 131–149). Hawthorne, NY: Aldine De Gruyter.

Brown, B.B. (2004). Adolescents' relationships with peers. In R.M. Lerner & L. Steinberg (Eds.), *Handbook of adolescent psychology* (2nd ed., pp. 363–394). New York: Wiley.

Carskadon, M.A., Vieira, C., & Acebo, C. (1993). Association between puberty and delayed phase preference. *Sleep*, *16*, 258–262.

Cicchetti, D., & Rogosh, F.A. (2002). A developmental psychopathology perspective on adolescence. *Journal of Consulting and Clinical Psychology*, *70*, 6–20.

Collins, W.A. (1990). Parent–child relationships in the transition to adolescence: Continuity and change in interaction, affect, and cognition. In R. Montemayor, G.R. Adams, & T.P. Gullotta (Eds.), *From childhood to adolescence: A transitional period? Advances in adolescent development, an annual book series*, Vol. 2 (pp. 85–106). London: Sage.

Dishion, T.J., Nelson, S.E., Winter, C., & Bullock, B. (2004). Adolescent friendship as a dynamic system: Entropy and deviance in the etiology and course of male antisocial behavior. *Journal of Abnormal Child Psychology*, *32*, 651–663.

Dunn, J. (1988). *The beginnings of social understanding*. Cambridge, MA: Harvard University Press.

Eccles, J.S. (2004). Schools, academic motivation, and stage-environment fit. In R.M. Lerner & L. Steinberg (Eds.), *Handbook of adolescent psychology* (2nd ed., pp. 125–153). New York: Wiley.

Eisenberg, N. (1992). *The caring child*. Cambridge, MA: Harvard University Press.

Farrington, D.P. (2004). Conduct disorder, delinquency, and aggression. In R.M. Lerner & L. Steinberg (Eds.), *Handbook of adolescent psychology* (2nd ed., pp. 627–664). New York: Wiley.

Fogel, A. (1993). *Developing through relationships: Origins of communication, self, and culture*. Chicago, IL: University of Chicago Press.

Ford, D.H., & Lerner, R.M. (1992). *Developmental systems theory: An integrative approach*. Newbury Park, CA: Sage.

Gottlieb, G. (1991). Epigenetic systems view of human development. *Developmental Psychology*, *27*, 33–34.

Gottman, J.M., McCoy, K., Coan, J., & Collier, H. (1996). *The specific affect coding system (SPAFF) for observing emotional communication in marital and family interaction*. Mahwah, NJ: Erlbaum.

Gottman, J.M., Murray, J.D., Swanson, C.C., Tyson, R., & Swanson, K.R. (2002). *The mathematics of marriage: Dynamic nonlinear models*. London: MIT Press.

Graber, J. (2004). Internalizing problems during adolescence. In R.M. Lerner &

L. Steinberg (Eds.), *Handbook of adolescent psychology* (2nd ed., pp. 587–619). New York: Wiley.

Graber, J.A., & Brooks-Gunn, J. (1996). Transitions and turning points: Navigating the passage from childhood through adolescence. *Developmental Psychology*, *32*, 768–776.

Granic, I. (2005). Timing is everything: Developmental psychopathology from a dynamic systems perspective. *Developmental Review*, *25*, 386–407.

Granic, I., & Dishion, T.J. (2003). Deviant talk in adolescent friendships: A step toward measuring pathogenic process. *Social Development*, *12*, 314–334.

Granic, I., & Hollenstein, T. (2003). Dynamic systems methods for models of developmental psychopathology. *Development and Psychopathology*, *15*, 641–669.

Granic, I., Hollenstein, T., Dishion, T.J., & Patterson, G.R. (2003). Longitudinal analysis of flexibility and reorganization in early adolescence: A dynamic systems study of family interactions. *Developmental Psychology*, *39*, 606–617.

Granic, I., & Lamey, A.V. (2002). Combining dynamic-systems and multivariate analyses to compare the mother–child interactions of externalizing subtypes. *Journal of Abnormal Child Psychology*, *30*, 265–283.

Granic, I., O'Hara, A., Pepler, D., & Lewis, M.D. (in press). A dynamic systems analysis of parent–child changes associated with successful "real-world" interventions for aggressive children. *Journal of Abnormal Child Psychology*.

Granic, I., & Patterson, G.R. (2006). Toward a comprehensive model of antisocial development: A dynamic systems approach. *Psychological Review*, *113*, 101–131.

Heath, R.A. (2000). *Nonlinear dynamics: Techniques and applications in psychology*. Mahwah, NJ: Erlbaum.

Hollenstein, T. (2005). Socioemotional development across the early-adolescent transition. Unpublished doctoral thesis, University of Toronto, Canada.

Hollenstein, T., Granic, I., Stoolmiller, M., & Snyder, J. (2004). Rigidity in parent–child interactions and the development of externalizing and internalizing behavior in early childhood. *Journal of Abnormal Child Psychology*, *32*, 595–607.

Hollenstein, T., & Lewis, M.D. (2006). A state space analysis of emotion and flexibility in parent–child interactions. *Emotion*, *6*, 663–669.

Johnson, S.L., & Nowak, A. (2002). Dynamical patterns in bipolar depression. *Personality and Social Psychology Review*, *6*, 380–387.

Kagan, J. (1998). Is there a self in infancy? In M. Ferrari & R.J. Sternberg (Eds.), *Self-awareness: Its nature and development* (pp. 137–147). New York: Guilford Press.

Keating, D.P. (2004). Cognitive and brain development. In R.M. Lerner & L. Steinberg (Eds.), *Handbook of adolescent psychology* (2nd ed., pp. 45–84). New York: Wiley.

Kopp, C.B. (1989). Regulation of distress and negative emotions: A developmental view. *Developmental Psychology*, *25*, 343–354.

Lamey, A., Hollenstein, T., Lewis, M.D., & Granic, I (2004). GridWare (Version 1.1). [Computer software]. http://statespacegrids.org

Larson, R., & Ham, M. (1993). Stress and "storm and stress" in early adolescence: The relationship of negative events with dysphoric affect. *Developmental Psychology*, *29*, 130–140.

Larson, R.W., Moneta, G., Richards, M.H., & Wilson, S. (2002). Continuity, stability, and change in daily emotional experience across adolescence. *Child Development*, *73*, 1151–1165.

Laursen, B., Coy, K.C., & Collins, W.A. (1998). Reconsidering changes in parent–child conflict across adolescence: A meta-analysis. *Child Development*, *69*, 817–832.

Lewis, M., & Michalson, L. (1983). *Children's emotions and mood: Developmental theory and measurement*. New York: Plenum Press.

Lewis, M., Sullivan, M.W., Stanger, C., & Weiss, M. (1989). Self-development and self-conscious emotions. *Child Development*, *60*, 146–156.

Lewis, M.D. (2000). The promise of dynamic systems approaches for an integrated account of human development. *Child Development*, *71*, 36–43.

Lewis, M.D. (2005). Bridging emotion theory and neurobiology through dynamic systems modeling (target article). *Behavioral and Brain Sciences*, *28*, 105–130.

Lewis, M.D., Granic, I., & Lamm, C. (2006). Neurocognitive mechanisms of emotion regulation and behavioral flexibility in aggressive children. *Annals of the New York Academy of Sciences*.

Lewis, M.D., Lamey, A.V., & Douglas, L. (1999). A new dynamic systems method for the analysis of early socioemotional development. *Developmental Science*, *2*, 457–475.

Lewis, M.D., Lamm, C., Segalowitz, S.J., Stieben, J., & Zelazo, P.D. (2006). Neurophysiological correlates of emotion regulation in children and adolescents. *Journal of Cognitive Neuroscience*, *18*, 430–443.

Lewis, M.D., Zimmerman, S., Hollenstein, T., & Lamey, A.V. (2004). Reorganization in coping behavior at 1 1/2 years: Dynamic systems and normative change. *Developmental Science*, *7*, 56–73.

Martin, C.L., Fabes, R.A., Hanish, L.D., & Hollenstein, T. (2005). Social dynamics in the preschool. *Developmental Review*, *25*, 299–327.

Paikoff, R.L., & Brooks-Gunn, J. (1991). Do parent–child relationships change during puberty? *Psychological Bulletin*, *110*, 47–66.

Richters, J.E. (1997). The Hubble hypothesis and the developmentalist's dilemma. *Development and Psychopathology*, *9*, 193–229.

Rosenblum, G.D., & Lewis M. (2003). Emotional development in adolescence. In G.R. Adams & M. Berzonsky (Eds.), *Blackwell handbook of adolescence* (pp. 269–289). New York: Blackwell.

Ruhland, R., & van Geert, P. (1998). Jumping into syntax: Transitions in the development of closed class words. *British Journal of Developmental Psychology*, *16*, 65–95.

Shannon, C.E., & Weaver, W. (1949). *The mathematical theory of communication*. Urbana: University of Illinois Press.

Simmons, R.G., & Blyth, D.A. (1987). *Moving into adolescence: The impact of pubertal change and school context*. New York: Aldine De Gruyter.

Simmons, R.G., Burgeson, R., Carlton-Ford, S., & Blyth, D.A. (1987). The impact of cumulative change in early adolescence. *Child Development*, *58*, 1220–1234.

Spear, L.P. (2000). The adolescent brain and age-related behavioral manifestations. *Neuroscience and Biobehavioral Reviews*, *24*, 417–463.

Steenbeek, H., & van Geert, P. (2005). A dynamic systems model of dyadic interaction during play of two children. *European Journal of Developmental Psychology*, *2*, 105–145.

Steinberg, L. (1990). Autonomy, conflict, and harmony in the family relationship. In S. Feldman & G. Elliot (Eds.), *At the threshold: The developing adolescent* (pp. 255–276). Cambridge, MA: Harvard University Press.

Steinberg, L. (2001). We know some things: Parent–adolescent relationships in retrospect and prospect. *Journal of Research on Adolescence*, *11*, 1–19.

Susman, E.J., & Rogol, A. (2004). Puberty and psychological development. In R.M. Lerner & L. Steinberg (Eds.), *Handbook of adolescent psychology* (2nd ed., pp. 15–44). New York: Wiley.

Thelen, E., Schoner, G., Scheier, C., & Smith, L.B. (2001). The dynamics of embodiment: A field theory of infant perseverative reaching. *Behavioral and Brain Sciences*, *24*, 1–34.

Thelen, E., & Smith, L.B. (1998). Dynamic systems theories. In W. Damon (Ed.), *Handbook of child psychology* (5th ed., Vol. 1). *Theoretical models of human development* (pp. 563–634). New York: Wiley.

Thelen, E., & Ulrich, B.D. (1991). Hidden skills: A dynamic systems analysis of treadmill stepping during the first year. *Monographs of the Society for Research in Child Development*, *56*(1, Serial No. 223).

Tomasello, M. (1995). Joint attention as social cognition. In C. Moore & P.J. Dunham (Eds.), *Joint attention: Its origins and role in development* (pp. 103–130). Hillsdale, NJ: Erlbaum.

Tryon, W.W. (1999). A bidirectional associative memory explanation of posttraumatic stress disorder. *Clinical Psychology Review*, *19*, 789–818.

Van der Maas, H.L.J. (1995). Beyond the metaphor? *Cognitive Development*, *10*, 621–642.

van der Maas, H., & Molenaar, P. (1992). Stagewise cognitive development: An application of catastrophe theory. *Psychological Review*, *99*, 395–417.

van Geert, P. (1994). *Dynamic systems of development: Change between complexity and chaos*. New York: Prentice Hall/Harvester Wheatsheaf.

van Geert, P. (1998). A dynamic systems model of basic developmental mechanisms: Piaget, Vygotsky, and beyond. *Psychological Review*, *105*, 634–677.

van Geert, P., & Steenbeek, H. (2005). Explaining after by before: Basic aspects of a dynamic systems approach to the study of development. *Developmental Review*, *25*, 408–442.

Wimmers, R.H., Savelsbergh, G.J.P., Beek, P.J., & Hopkins, B. (1998). Evidence for a phase transition in the early development of prehension. *Developmental Psychobiology*, *32*, 235–248.

Zahn-Waxler, C., & Radke-Yarrow, M. (1982). The development of altruism: Alternative research strategies. In N. Eisenberg (Ed.), *The development of prosocial behavior* (pp. 109–137). New York: Academic Press.