Dynamic Systems Approaches: Cool Enough? Hot Enough?

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ABSTRACT—***This article outlines key insights and methods from the dynamic systems (DS) approach to development, considers successes and failures of the approach thus far, and suggests future directions, especially in the area of developmental neuroscience. It begins with a brief review of major contributions by scholars who have defined the field. Then it reviews the author's theoretical work on self-organizing personality development, cognition–emotion interactions, and individual phase transitions that correspond with more global developmental changes. Finally, it discusses empirical work by the author and his colleagues using* state space grids *to measure emotional and interpersonal stability across development, and then highlights neuroscientific applications. The article concludes that the DS perspective needs to be "cool" enough to attract other developmentalists, yet "hot" enough to move the field forward, and that these goals are definitely worth pursuing.***

KEYWORDS—*dynamic systems; cognition-emotion; personality development; neuroscience*

I was a graduate student trying to understand cognition–emotion relations in development, trying to figure out how stages could coexist with incremental learning, trying to reconcile normative developmental patterns with the jungle of individual styles. None of it was working. The best theories of normative development ignored individual differences. Stage theorists and learning theorists were shooting at each other, and cognition and emotion appeared to describe two distinct species. I was looking for integration, for a grand unified theory, or at least a macroscopic model, that could handle complexity and still remain principled and rule based. I was looking for some way that cognition could advance predictably yet be pushed around by emotion. I wondered how development was even possible. How did it work? How do people change? How do they stay the same? And why don't conventional approaches do a better job of solving these mysteries? For example, why are predictions from precursors to outcomes either very small, accounting for a tiny percentage of the variance, or boringly obvious, as when trouble at one age predicts some disadvantage at a later age?

Then I went to a lecture on fractals and found a book on self-organizing systems. These two phenomena were somehow related! Simple feedback mechanisms could produce massive complexity without any particular prescription. I discovered developmentalists who were working with this stuff. They did not all come to the same conclusions, but they were resonating to the same conceptual beat: patterned forms emerging from variability. I played with cellular automata that seemed to model living beings. I trained my video camera on its own output and watched beautiful patterns appear—elaborate images arising almost magically from a feedback process. I started to get it: This was development! And I began to apply these principles to everything I had studied and wanted to study. I was hooked.

In this article, I outline new insights and methods provided by the dynamic systems (DS) approach to development, what this approach has achieved and failed to achieve, and where it might go next. I go into some detail on work by my colleagues and me, but I also discuss the contributions of investigators who have helped define the field. I am still hooked on the DS approach, although I am not completely satisfied with what it has accomplished so far. A lot of work remains to be done. For the DS approach to fulfill its potential, it must continue to be "cool" enough to attract other developmentalists with novel methods and compelling models. Yet it must also be "hot" enough to move the field forward by supplying powerful analytical tools

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that drive substantive advances, not just flashy new appearances.

CONTRIBUTIONS

It is difficult to summarize 20 years of DS thinking and research in developmental psychology, but it is possible to discern several broad lineages that began to take shape in the late 1980s and early 1990s. The most influential have been Thelen and Smith's research program and the work of several Dutch developmentalists. Among the "Dutch Masters," Paul van Geert has been the central promoter of DS theory and methods. He introduced the concept of self-organization as a critical construct for explaining the emergence of order in development, and he integrated this and other DS constructs, including phase transitions and equilibria, with classical elements of Piagetian stage theory. van Geert and his colleagues also devised innovative empirical methods for the DS analysis of diverse content domains, from linguistic development (Ruhland & van Geert, 1998) to infant distress (de Weerth & van Geert, 2000). Much of this work used an iterative mathematical formula that produced growth curves resembling developmental time series. Finally, van Geert (1991, 1994, 1998) challenged the developmental community to think dynamically in order to generate realistic models of change. Another Dutch Master, Han van der Maas, specialized in applications based on catastrophe theory, and he contributed to the developmental literature through precise and testable models for phase transitions and other DS constructs (e.g., van der Maas, 1998; van der Maas & Molenaar, 1992). Peter Molenaar applied various mathematical and statistical methods to characterize intraindividual variation and other relevant constructs (e.g., Raijmakers & Molenaar, 2004).

While the Dutch Masters were playing with numbers, Esther Thelen and Linda Smith established their own DS empire in North America. Alan Fogel had close ties with Thelen at first, but he established his unique lineage based on the microdevelopmental coding of mother–infant interactions. Fogel's major contribution was to demonstrate the value of dyads as units of developmental analysis, while analyzing the microdevelopmental behavioral sequences that gave rise to dyadic patterns. However, Thelen and colleagues' work soon evolved into a broad theory of cognitive development. Like van Geert, they emphasized self-organization or emergence as a root concept but elaborated other DS constructs such as "soft assembly" or context-based emergence, attractors on a state space, interrelated time scales, and the importance of variability (or stochasticity) as a creative springboard for developmental emergence. Unlike van Geert, they eschewed stages as superordinate structures, which they believed were extraneous in models of self-organization. As Witherington (2007) proposed, they emphasized that structures at all time scales, from cognitive acts to stable abilities, arise from the same real-time emergent processes, thus invoking theoretical homogeneity at the expense of an articulated developmental framework.

In the early stages of this work, Thelen and Ulrich (1991) introduced DS thinking through a set of carefully laid out steps of analysis and modeled the development of infant walking using this formula. In a landmark volume, Thelen and Smith (1994) compiled further empirical methods for measuring emergence without mathematics. Their work on the A-not-B error, language development, and motor development throughout the 1990s culminated in "dynamic field theory," a model of action guided by perceptual processes mediated by the coupling of neural components (Thelen, Schöner, Scheier, & Smith, 2001). This research program is now spearheaded by John Spencer, who describes it in detail elsewhere in this issue (Spencer, Perone, & Buss, 2011).

My own work was inspired by both the Dutch and American lineages, and DS work in cognitive psychology, biology, and other disciplines, including Varela and colleagues' brilliant account of self-organization in an embodied mind (e.g., Varela, Thompson, & Rosch, 1991). I was also taken with an idea from Killeen (1989), who saw human behavior as "a trajectory through a field of attractors." Extending this theme to the study of socioemotional development, I saw that such attractors exist in real time, where they represent skills, moods, or goal states, but also in developmental time, where they can represent personality styles that endure for years or decades. To model the feedback dynamics that produce attractors in personality development, I described the relations between emotions and cognitive appraisals as positive feedback loops, in which an emotion (such as anger) augments appraisals (such as goal blockage) that magnify those very emotions. In theoretical articles published between 1995 and 2001, I described personality development in terms of cognition–emotion feedback, stabilized by coupling, or reciprocal constraints, among multiple psychological components. This scheme led to the idea of branching pathways of individual development, as personalities became increasingly articulated and refined, although progressively constrained by their own histories. As Figure 1 shows, it is possible to represent a pathway describing a specific trajectory against a background of potential pathways. The final touch was to model bifurcations in this branching trajectory as phase transitions that corresponded with developmental stage transitions defined by existing theories. Figure 2 depicts a theoretical model of phase transitions in individual development superposed on a series of cognitive-developmental stage shifts (Panel A), as well as empirical support for this model from a study of socioemotional changes at 18–20 months (Lewis, Zimmerman, Hollenstein, & Lamey, 2004), a developmental shift that Case (1985) and others described (Panel B).

The analysis of phase transitions in socioemotional development became an ongoing project for my colleagues, Isabela Granic and Tom Hollenstein, and me. But to perform these analyses, it was necessary to devise a methodology capable of capturing the behavioral state space at any given point in development. The Dutch Masters had cornered the math market, and Thelen, Smith, and Fogel used either qualitative analyses or

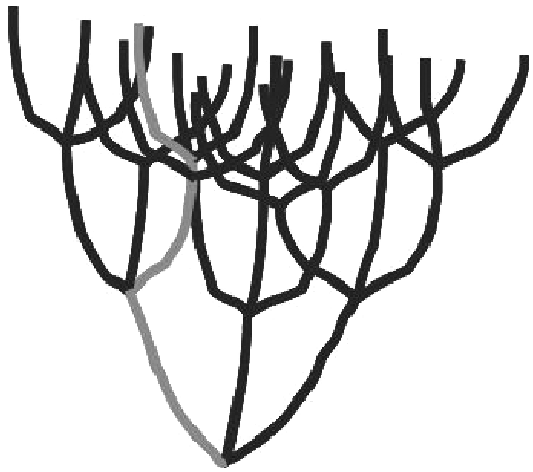

Figure 1. A branching pathway of individual personality development, constituting increasingly articulated habits that are constrained by previous branchings. The pathway describing a specific trajectory is represented against a background of potential pathways.

simple descriptive statistics, but I wanted to cut a path between these extremes, one that would prove accessible to other developmentalists yet be sufficiently rigorous to test hypotheses. Alex Lamey and I developed the "state space grid," a matrix of cells representing the sequential values of two time-locked ordinal variables, one shown on the x-axis and the other on the y-axis. Within this grid, we could draw the trajectory of behavior in real time as a line traveling from one cell to another. Each cell stood for a particular point in the behavioral state space (such as moderate gaze aversion coupled with low distress), so that the trajectory of behavior might stop in one cell (or cluster of cells) or return to it repeatedly, suggesting an attractor. We tested these patterns statistically against base-rate probabilities. Moreover, we could trace changes in the value of each cell, from one grid to another, across a series of longitudinal waves, producing a metalevel time series depicting stable periods and developmental phase transitions. Here, then, was a quantitative map of a developmental trajectory, based entirely on observational data. In the past few years, the grid method has evolved into a standalone software application called GridWare (Lamey, Hollenstein, Lewis, & Granic, 2004). GridWare is highly modifiable: Through use of point-and-click tools, it produces evocative graphics for exploring attractor landscapes, but it also outputs variable values into standard spreadsheets for statistical analysis.

I first authored three articles using grids to assess attractors and phase transitions in infants and toddlers (Lewis & Cook, 2007; Lewis, Lamey, & Douglas, 1999; Lewis et al., 2004). The upshot of these studies was that socioemotional habits went through statistically defined phase transitions at the age of cognitive stage shifts (e.g., Figure 2B) identified by neo-Piagetian theory (Case, 1985, 1992), but the content of these habits differed across individuals. Granic and Hollenstein went on to search for socioemotional transitions at other ages, finding discontinuous

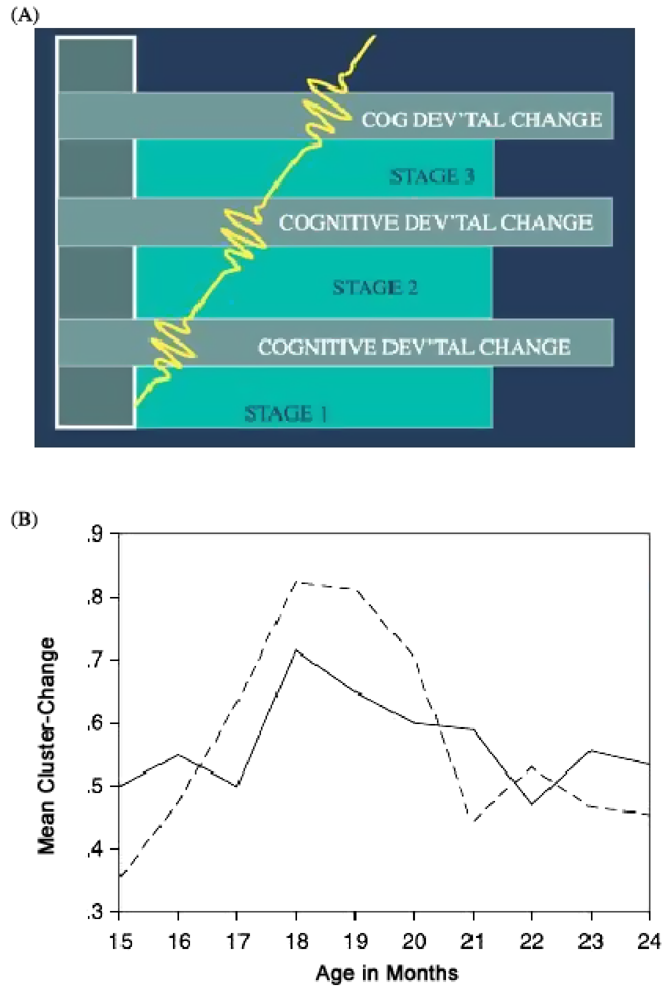

Figure 2. Panel A: Stable periods interspersed by phase transitions in a developmental trajectory, shown against a background of normative developmental stages. The change from one normative stage to the next corresponds with behavioral fluctuations characteristic of a phase transition in the development of a habit or skill. Panel B: Month-to-month variability in two infant–mother variables (Lewis, Zimmerman, Hollenstein, & Lamey, 2004), demonstrating the predicted increase in behavioral fluctuations at 18–20 months, the average age of change between the sensorimotor and interrelational stages in Case's (1985) theory. Grid configurations were cluster analyzed, and the y-axis represents the mean cluster-change score (presence or absence of change between clusters), with higher values depicting greater mean cluster-change or higher variability.

change in parent–child interactions at the cusp of adolescence (Granic, Hollenstein, Dishion, & Patterson, 2003), an age when emotional intensity affects parent–child flexibility (Hollenstein & Lewis, 2006). However, most of their work has focused on children diagnosed with behavior problems. They used state space grids to differentiate the interpersonal habits of subtypes of aggressive children (Granic & Lamey, 2002), predict developmental psychopathology on the basis of early parent–child interactions (Hollenstein, Granic, Stoolmiller, & Snyder, 2004), and assess changes in flexibility and emotional repair due to treatment (Granic, O'Hara, Pepler, & Lewis, 2007). Other developmentalists have adopted state space grids to assess socioemotional behavior in normal (Martin, Fabes, Hanish, & Hollenstein, 2005) and atypical (Dishion, Nelson, Winter, & Bullock, 2004) peer interactions. Common to all of the studies using grids is the fine-grained evaluation of behavioral variability. As modeled by Granic and Patterson (2006), healthy development relies on socioemotional variability within and between interactants, not positive emotion, as many assume. Moreover, the converse of variability—socioemotional rigidity—appears to predict developing psychopathology, even in the absence of overt negative emotion.

My own research has shifted to the realm of developmental neuroscience. It seemed that one exciting way to assess psychological self-organization was to analyze the development of networks emerging from synchrony among neuronal populations. We have made some progress in the theoretical modeling of cortical dynamics underpinning emotion and its regulation (Lewis, 2005a, Lewis, 2005b; Lewis & Todd, 2007). For one thing, an analysis of brain activity suggests that it is impossible to segregate "cognition" and "emotion" in neural processes, so these are the wrong categories for a description of coupling. Much finer distinctions are necessary, and we can trace these in corticolimbic networks that are distinguished and categorized according to their unique functions. Yet our empirical work is only now moving beyond traditional neuroscientific methods, such as averaging EEG epochs and extracting event-related potentials. The next step for us is the analysis of cortical power and phase synchrony, techniques I return to at the end of this article.

EVALUATION

The overall advancement of developmental research informed by DS ideas has been consistent but slow. There has surely been progress, but it has fallen short of some of our hopes and projections. The number of DS publications in developmental journals has increased in a somewhat linear fashion, but I have not seen the exponential growth spurt we had hoped for. van Geert addresses the implications of this disappointing outcome elsewhere in this issue; he detects an unwillingness on the part of developmentalists to grapple with new approaches in place of their comfortable conceptual and empirical habits. Spencer et al. (2011) appears much more optimistic about the fulfillment of the promise of DS approaches.

My own view is that the limited progress of the DS paradigm may be forgiven in light of its lofty goals. Unlike other research programs in developmental psychology, the DS program construes itself as a metatheoretical framework destined to transform the entire field (Witherington, 2007). Some of us expected that the root concept of emergence (or emergentism) would replace the conventional doctrines of developmental psychology, including innatism, behaviorism, and constructivism (Lewis, 2000). Speaking as one of the converted, it is difficult for me to imagine any other way to conceptualize development except as the self-organization of increasingly complex forms, such as schemas, skills, and emotional habits, through the recursive interactions of psychological components. Yet many developmentalists remain unconvinced. They continue to highlight conditioning and inheritance as key causal mechanisms of developmental outcomes—and although each is important, there is much about development that they cannot explain. Empirical methods have also remained largely unperturbed. Although most developmentalists find the DS approach "interesting," even "fascinating," they continue to rely on time-honored methods based on the general linear model. We might conclude that current DS methods are "cool" enough to attract attention but not "hot" enough to penetrate the empirical habits of our field. Another unique disadvantage of DS approaches is their diversity. Although they aim for the same grand conceptualization of development, they cannot agree on how to get there. In fact, there have been conceptual rifts within the DS camp that hamper the emergence of a coherent framework (van der Maas, 1995; Witherington, 2007). Thelen and Smith wanted to dethrone Piaget, considering him the progenitor of an outdated structuralist doctrine (Witherington, in press). For the Dutch Masters, Piaget *was* an early DS theorist, highlighting the relation between developmental equilibria and qualitative shifts. To make matters worse, every DS method seems to alienate some subset of developmentalists. The mathematical approaches are unattractive to those who shy away from formulas in psychological writings. The qualitative approaches are often unappealing to those who demand quantitative rigor. Even our own grid method is catching on with agonizing slowness, perhaps because it is just so foreign.

Yet the slow pace of change should not be entirely surprising. Dynamic thinkers should be the first to recognize that complex systems—including the conceptual habits of a scientific subdiscipline—resist change until they can no longer absorb perturbations. In fact, given this resistance, it is heartening to consider the inroads that DS ideas and methods have made in the discipline at large. Here, I list a number of examples, as a means of characterizing our impact to date.

Thelen and colleagues pitched many novel concepts, but one of the most appealing was the idea that cognition and development take place, not in the head, but in the interactions between the mind and the environment (e.g., Thelen & Smith, 1994). This idea has infiltrated many bastions of development, including neo-Piagetian theory. Kurt Fischer and colleagues (e.g., Fischer & Bidell, 2006; Rose & Fischer, 1998) adopted a central dynamicist plank in their stage theory. On the basis of van Geert's formulas, Case et al. (1996) also began to tinker with dynamic systems models of stage transitions. Neural network modeling has penetrated developmental psychology in various ways, and its principles are highly intertwined with the tenets of self-organizing dynamic systems (Elman et al., 1996; see Spencer, Thomas, & McClelland, 2009, for a review, synthesis, and new directions). Neural networks provide one vehicle by which developmentalists have come to recognize relations among iteration, coherence, and emergent forms. Developmentalists once thought that behavioral genetics would supply all the answers to understanding development. But the recurring ubiquity of interaction effects has trounced any simple connection between genes and outcomes. Interaction effects have become a staple of developmental theory and research, as epitomized by the work of Suomi, Gottlieb, Caspi and Moffit, and others. DS thinkers have come to eschew a "nature versus nurture" dichotomy in developmental explanations (e.g., Spencer et al., 2009), and authors such as Lerner, Sameroff, Spencer, Oyama, and Lickliter have explicitly used DS terms and concepts to frame interactions between biology and environment (e.g., Lickliter & Honeycutt, 2003). DS ideas are also highly compatible with systemic approaches to neuroscience. Besides the work of Thelen, Smith, Spencer, and our own group, neuroscientists interested in development have absorbed DS concepts into their theories and methods (e.g., Freeman, 1995; Tucker, 1992). Finally, our own work represents a narrow tributary of the DS stream, but it has enjoyed some impact in the field of developmental psychopathology, where mainstream researchers such as Patterson and Dishion have applied our methods and models to feedback, synchrony, and interpersonal flexibility in the etiology of behavior problems.

NEXT STEPS

It seems that some of the most important challenges and opportunities for DS approaches to development lie in the fusion of developmental psychology with neuroscience. The human brain is the epitome of a self-organizing system. In particular, cortical and limbic structures undergo massive synaptic reorganization over a protracted period of development, through the iterative cycling of perception, cognition, and action. An emphasis on the brain as a multilevel, multiscale system, characterized by recursive processes and emergent structure, provides many advantages over models that focus on local activities and linear computational sequences. For example, systemically oriented theorists demonstrate that cognition, emotion, developmental change, and consciousness itself are products of patterns emerging at many scales in a self-organizing synaptic architecture (e.g., Buzsáki, 2006; Freeman, 2000; Lewis, 2005a, 2005b; Tucker, 2007). At the scale of real time, neuronal populations in the cortex become spontaneously synchronized to form networks that have distinct functions (e.g., Seeley et al., 2007). At the developmental time scale, long-distance cortical networks converge from the interactions of component populations over many episodes of learning (e.g., Fair et al., 2009). At these and intermediate scales, all the mechanisms of synchronization, emergent form, stabilization, and recurrence that characterize dynamic systems are evident in the concrete interactions of biologically real entities. Thus, the brain is a natural forum for studying the dynamic mechanisms of human development and for demonstrating the advantages of the dynamic approach when it comes to modeling extraordinary complexity.

This realization led me to switch from behavioral research to developmental neuroscience in my own work. Psychological terms such as *cognitions, emotions, perceptions, schemas, affects*, and so forth seemed too vague to permit a detailed analysis, especially when it came to real-time dynamic processes. Moreover, available technologies can directly measure the synchronization and coupling of neuronal systems and subsystems. Time series of fMRI data points can assess functional connectivity, and high-density EEG can directly measure phase synchrony and cortical coherence. Both techniques are capable of charting network formation, coherence, and increasing efficiency as development ensues. I believe that the integration of these "cool" methods with psychological measures will facilitate DS modeling that is highly precise, testable, and accessible to multiple domains, thus "hot" enough to move us toward fine-grained theories of human development firmly anchored in neuropsychological data.

Neuroscience is not the only road to Rome, and many other applications can advance DS thinking and methods. These include fine-grained coding of behavioral data (e.g., Hollenstein & Lewis, 2006); mathematical modeling based on catastrophe theory, Markov models, and so forth; statistical methods such as event history analysis and recurrence quantification analysis (Stephen, Dixon, & Isenhower, 2009) that can identify phase transitions, attractors, and so forth; and computer generated models, including those of Spencer et al. (2011) and van Geert (2011), that are informed by and compared with real behavioral or neural data. The other authors in this issue will elaborate further on some of these approaches. But I think we all agree that the DS paradigm must continue to be "cool" enough to attract developmental psychologists with its fresh insights and novel techniques yet strive to become "hot" enough to deliver robust findings, consistently and convincingly, through powerful analytical tools.

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