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The importance of dynamic systems approaches for understanding development [☆]

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Abstract

We outline the nature of dynamic systems, both linear and nonlinear, and we review dynamic systems principles that apply well to various aspects of human development, including the emergence of new forms, phases of stability and instability, continuous and discontinuous change, and differentiation among individual trajectories. We then document the growth and popularity of dynamic systems approaches for understanding a diverse array of developmental domains. Finally, we acknowledge the contribution and impact Esther Thelen has made in this area of developmental science, and dedicate this special issue to her memory.
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Why a special issue on dynamic systems? First and foremost it is our way of honoring the memory of a friend and colleague, Esther Thelen. Esther was a visionary who pioneered the use of dynamic systems approaches for understanding development, particularly early motor development. Her work towards establishing a dynamic theory integrating action, perception, and cognition was tireless and has inspired many others to use dynamic systems concepts and methods in their own research domains.

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Second, the dynamic systems bag of tricks seems to include several obvious tools for use when trying to understand the many intricacies of development. Not only does such an approach permit theoretical statements about the development of social entities such as societies and groups, but also about individuals within those societies, specific components of individuals (e.g., personality, emotion, neurobiology), and microanalytic aspects of those components (e.g., a single neural cell and its interconnections with other cells). In other words, the dynamic systems approach solves the "levels" problem, or rather avoids it by acknowledging that development is multilayered.

Similarly, dynamic systems treatments often avoid the so-called "stage" debate because outward behaviors that appear to be stage-like can be explained by continuous changes in the underlying components responsible for those behaviors (see Courage & Howe, 2002). Perhaps most important is that dynamic systems concepts are about change and transition, the so-called "stuff" of development. Developmental psychologists are not simply interested in the stable states achieved by individuals along their lifespan, but also about the mechanisms of change that lead from one state to the next. Whether this change is represented continuously in time or as a series of stages with abrupt transitions, dynamic models focus our attention on change.

Dynamic systems are also self-organizing. Quite simply, all developmental outcomes are a result of the spontaneous emergence of higher-order structures from the recursive interactions among simpler components. Indeed, self-organization is viewed across many sciences as the primary "driver" of growth and change throughout the natural world (see Lewis, 2000). In the context of human behavior, developing organisms can be viewed as high-dimensional systems consisting of numerous genetic, physiological, and psychological attributes. Behavior results from the interaction of these (and other) attributes with the current environment, as contextualized by the task at hand. This is the essence of self-organization in real time (e.g., seconds or minutes). As Thelen and Ulrich (1991, p. 24) note, "There is no single element that contains the prior instructions for the behavioral performance ...the essence of the behavior lies in neither the organism nor the environment alone ... (and) neither has logical priority in explaining behavior or its changes." However, the emergence of skills, schemas, personality patterns, and so on represents configurations that have crystallized over many occasions, yielding developmental forms or habits. These habits can be modeled as attractors for behavioral states in real time, as detailed later. This is the essence of self-organization in developmental time (e.g., months or years). Thus, ontogeny cannot be considered hard-wired in any sense, but rather emergent, unpredictable, and always coupled with environmental events.

But what exactly is a dynamic system? To answer this, let us contrast a static system with a dynamic system. In static systems, ones that are all too frequently encountered in mainstream developmental psychology (also see van Geert & Steenbeek, this issue), a particular outcome (e.g., a mental state, friendship, depression) depends exclusively on the value of variables that affect the system at a particular time. That is, the outcome is independent of events that occurred earlier in time Eq. (1) is static

$$x_t = f(a, b, c, \ldots), \tag{1}$$

where x is the measured outcome at time t and $a, b, c, \ldots$ refer to the values of variables that affect the outcome at time t. However, a system is dynamic if the value of x generated at time t depends on its history (or values at earlier times). That is, the term *dynamic* is synonymous with phrases such as "time evolution" (e.g., Luenberger, 1979). Eq. (2) is dynamic

$$x_t = f(x_{t-1}, a, b, c, \ldots), \tag{2}$$

where the variables are the same as Eq. (1) with the exception of x_{t-1} which represents the state of the system at an earlier time. Dynamic systems pervade our everyday life and include examples as mundane as altering the temperature in one's home (e.g., the energy required to raised the temperature by 10° at time t depends on the ambient temperature at time $t - 1$). They are also pervasive in many scientific disciplines (again linking our developmental science to the other sciences) and arise in physical systems, social systems, and life systems (Luenberger, 1979).

Many of these simple systems can be explained using linear dynamic terms. That is, the state of a system at time t depends on a linear combination of earlier states. More complex systems are modeled using a nonlinear combination of earlier states. Frequently these latter systems settle into patterns that involve one or more points called attractors. The behavior of the system depends on its initial starting conditions and can change rapidly at first such that it may "overshoot" its eventual stable pattern or attractor, oscillate for a while, and finally arrive at a stable point. Obvious development examples abound and range from early motor development (e.g., reaching, grasping, crawling, walking) to cognitive and linguistic development (e.g., Howe & Rabinowitz, 1994; Ruhland & van Geert, 1998) and, as this special issue attests, most other domains of development as well.

These models are ideally suited to account for development because they can accommodate the continuities and discontinuities that make up development. As growth occurs and different environments are encountered, the stability of a developmental form (a particular pattern of attractor states) can be altered such that some states become less preferred and less reliable while others become more stable and dominant. These discontinuities are captured in dynamic systems models using the notion of a phase transition. Specifically, as one or more components of the developing system changes beyond a particular threshold, the entire system may become reorganized in an apparent qualitative shift. The development of a dynamic system can be viewed as a series of shifts between periods of stabilization and periods of destabilization. Stable phases are characterized by a field of attractors that remain in place over occasions, guiding behavior in predictable ways, whereas unstable phases are characterized by weak or changing attractors, such that behavior becomes less predictable and more novel (Thelen & Smith, 1994). Events that disrupt stable phases are called driving forces and can originate externally (e.g., war, famine, abuse) or internally (e.g., hormonal changes, depression, heart attack). As Thelen (1989) pointed out, viewed dynamically, behavioral instability is particularly important for understanding development because it is frequently associated with transitional events.

Nonlinear dynamic models also account for marked individual differences in growth curves. This is because the equations that describe system change are sensitive to the initial starting values—or, in behavioral terms, the trajectory of the system depends on its initial conditions. If two sets of initial conditions are even slightly different, in nonlinear dynamic systems, their states will quickly diverge. In other words, growth curves describing the development of two individuals, each characterized by the same parameters but with different initial starting values, would show marked differences over several iterations. Although these systems are classically described as deterministic, inasmuch as the parameters of the system can be known, the state of any two *complex* dynamic systems can never be measured with precision, hence differences in their developmental trajectories can never be mapped out in advance.

Although mathematical rigor may be a prerequisite for some approaches to dynamic analysis, others have effectively utilized the general guiding principles of dynamic systems to design studies that document dynamic change using more traditional analytic techniques. Still others have developed new methods of analyses for studying dynamic change, ones that are perhaps more easily applied to behavioral data than the more daunting mathematics associated with nonlinear dynamic models (e.g., Lewis, Lamey, & Douglas, 1999). Thus, many approaches are available within the dynamic systems bag of tricks, making it relatively accessible to developmentalists of different persuasions.

With all of the advantages associated with the use of dynamic systems models for understanding development, the application of such models might be considered an obvious preference for discerning researchers. But have dynamic systems approaches become as popular as one might have predicted? A little over a decade ago one of us (MLH) put together a symposium on dynamic modeling of cognitive development, one that was published as a special issue of the *Journal of Experimental Child Psychology* (Volume 58, Issue 2). In the last article of that issue, Bogartz (1994) was asked to comment on the future of dynamic systems approaches to development, whether they would "live or die?" He said "On the basis of history, current proclivities of active researchers, and current quantitative training of psychology students, my bet would have to be that this approach will probably fade from the scene or at best remain a little island of activity restricted to a small group of interested parties" (Bogartz, 1994, p. 314). As the articles in this issue of *Developmental Review* attest, such a prognostication turns out to be an underestimate. More than a decade after that special issue, the articles contained here deal not only with the dynamics of cognitive development (Smith, this issue), but also with neurological development (Lewis, this issue), social development (Martin, Fabes, Hanish, & Hollenstein, this issue), emotional development (Camras & Witherington, this issue), personality development (Nowak, Vallacher, & Zochowski, this issue), and developmental psychopathology (Granic, this issue). Indeed, there are even claims that there exist at least two "schools" of dynamic systems modeling (van Geert & Steenbeek, this issue), and there appear to be other groups who work quite independently of either.

Nevertheless, dynamic systems approaches to development remain a clear minority. There has been a great deal of complaining in developmental journals about the constraints of conventional developmental approaches, including static or linear models and the use of averages rather than time-sensitive process accounts, and many developmentalists have espoused the value of systems thinking in theoretical articles (see Cicchetti & Cohen, 1995; Sameroff, 1995; Sroufe & Rutter, 1984). Yet most developmentalists continue to use conventional experimental designs and statistics to carry out their research (Granic & Hollenstein, 2003). We think this is because the trajectory of developmental psychology, like other dynamic systems, tends toward stability much of the time. Researchers stick to well-established habits of thinking and working, and their students acquire the same habits, often because that is the easiest road to publication and career advancement. Although no one should be blamed for being a creature of habit—a self-organizing universe demands no less of any viable organism—we hope Esther Thelen's pioneering vision of development, with some help from this special issue, will inspire other developmentalists to explore what is still, to many, a new terrain. Thelen was not afraid to defy conventional thinking wherever she came across it. She gently scolded developmentalists for sticking with principles of development that were, to her mind, outdated, confining, or simply wrong. She went on to map out a theory of development, along with her close colleague, Linda Smith, that recognized the child as an emergent self-organizing system, continuously changing or stabilizing in interaction with an environment, rather than a trajectory programmed by genetics, normative stages, or any other static variable. She showed us that breaking from conventional theory and method really does open up new avenues of understanding and scientific knowledge. We hope that, by demonstrating a wide variety of dynamic systems approaches to diverse developmental domains, the articles featured in this special issue will motivate and guide other researchers to explore this new terrain.

If that hope is realized, then Bogartz (1994, p. 314) may eventually be seen as having been more correct when commenting about his prediction, "That is the kind of remark that gets quoted with a snicker 20 years later when the approach is flourishing." Thanks to the hard work and dedication of many developmental scientists, but particularly Esther Thelen, dynamic systems approaches to understanding development may yet attain such a future state.

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