CHAPTER 1

Developmental Systems Theory and Methodology

A View of the Issues

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There exists a long tradition in theoretical psychology and theoretical biology in which developmental processes are explained as the result of self-organizing processes with emergent properties that have complex, dynamic interactions with environmental influences. The general denotation for this tradition is *developmental systems theory*. Important contributions to developmental systems theory include Ford and Lerner's (1992) integrative approach, based on the interplay between intraindividual variation and interindividual variation and change; Gottlieb's (1992, 2003) theoretical work on probabilistic epigenetic development; and Overton's discussions of relational metatheory and relational developmental systems theories (RDST; e.g., Overton, 2010, 2012; Overton & Müller, 2012).

Oyama, Griffiths, and Gray (2001) present a compilation of contributions of developmental systems theory to theoretical biology and, in turn, both the 1998 and the 2006 editions of the *Handbook of Child Psychology* (Damon, 1998; Damon & Lerner, 2006) devote the first volume of the four-volume work to theoretical models of human development; most of the theories represent variants of developmental systems theories. Indeed, in his introduction to the 2006 edition of this volume, Lerner (2006) notes that developmental systems models are at the cutting edge of theory in developmental science. This genre of theory frames as well the presentations in other major compendiums in developmental theories, for example, the second and third editions of the *Handbook of Adolescent Psychology* (Lerner & Steinberg, 2004, 2009), the two volumes of the *Handbook of Life-Span Development* (Lamb & Freund, 2010; Lerner & Overton, 2010), and the *Handbook of Developmental Science, Behavior and Genetics* (Hood, Halpern, Greenberg, & Lerner, 2010).

Accordingly, the tenets of developmental systems theory are well established as the superordinate developmental frame in contemporary developmental science. In addition, there are strong conceptual links between these theories and other contemporary theoretical models, such as dynamical systems, biological systems theory, and artificial neural networks (e.g., connectionism). However, researchers' interest in such theories has been limited by inadequate methods of measuring and analyzing change in continuous time-dependent streams of multivariate data. Such methods are necessary in decisive empirical tests of theoretical predictions derived from developmental systems theory. Impressive progress has been made in implementing developmental systems in sophisticated simulation programs (cf. Spencer, Thomas, & McClelland, 2009); yet these simulation models can only indirectly address the empirical validity of developmental process models. The ultimate test of theoretical models in empirical science is to fit models directly to appropriate empirical data.

Only recently have the required mathematical–statistical tools become available to fit developmental systems models directly to intensive measurements of developmental processes (for overviews, see Molenaar & Newell, 2010; Newell & Molenaar, 1998). These new modeling tools are predominantly based on dynamic systems modeling, having roots in applied nonlinear dynamics, computational engineering, econometrics, and statistical signal analysis. Initial applications of these tools have, for instance, resulted in major restructuring of (connectionistic) simulation programs of sudden qualitative transitions in development (cf. van der Maas & Raijmakers, 2009). The combination of advanced developmental systems theoretical modeling and sophisticated statistical–methodological approaches of empirical validation holds the potential to yield a powerful new paradigm for social science and medicine (cf. Schwartz & Collins, 2007).

In its most elementary form this new paradigm is characterized by the use of intensive measurements of single subjects (or patients) in real time and in their natural environments, often by means of advanced sensoring techniques. The data streams thus obtained are analyzed by means of recursive dynamic modeling techniques in order to (semi-)continuously assess and optimally guide the psychological, biobehavioral, and/or disease processes of interest. It has been demonstrated recently (Molenaar, 2004, 2007) that this intensive subject-specific data acquisition and dynamic modeling, which constitutes the first level of the new paradigm prior to pooling across subjects, yields powerful explanatory process models.

In order to propel forward the innovative integration of developmental systems theory with state-of-the-art statistical dynamic modeling tools, we organized the Conference on Inductive Developmental Systems Theory. During the conference, lively interactions took place that inspired some of the contents of the present *Handbook* and initiated further collaboration among the participants and colleagues beyond those at the conference. At the theoretical level, several chapters present important extensions of developmental systems theory, captured under the denotation *relational developmental systems*. At the level of inductive dynamic systems theory, many chapters present innovative applications of powerful statistical techniques to real and simulated time-dependent data streams in order to test theoretical predictions derived from developmental systems theory.

The Plan of the *Handbook*

We conclude this brief introductory chapter with short characterizations of each chapter in the *Handbook*. This section presents chapters that discuss key features and conceptual implications of relational developmental models of human development.

Willis F. Overton, in a chapter that constitutes a keynote presentation for the *Handbook*, builds on his prior discussions of relational developmental systems and focuses on methodological issues. He notes that if one's approach to methodology assumes that development is the systematic study of changes in intraindividual variability, intensive assessment, multivariate, within-subject methods and designs emerge and become critical. He points to the ideas of Nesselroade and Molenaar (2010, p. 31) that clearly articulate this point:

> Attention to intraindividual variability leads to favoring some kinds of research designs over others, how and what one measures, and the data analyses one performs. Even more fundamentally, intraindividual variability concerns help to delimit the very way one formulates his or her research questions and the manner in which one conceptualizes and deals with fundamental scientific matters such as prediction and generalizability. These latter concerns, in turn, rightfully have strong "trickle-down" effects on the design, measurement, and modeling efforts of students of development.

Accordingly, Overton argues that the "trickle-down" effects Nesselroade and Molenaar describe are real and important, but the sources of these effects begin much further upstream. He traces these effects to their headwaters, located in the highly abstract conceptual space of metatheory, and from there through their tributaries of various developmental conceptual models and theories, and to specific methods.

In the next chapter, G. John Geldhof and colleagues provide an illustration of the use of relational developmental systems ideas in regard to a specific portion of the life span—that is, adolescence—and note the methodological issues and implications of using relational developmental systems ideas for the study of this age period. The authors note that interest in the strengths of youth, the plasticity of human development, and the concept of resilience coalesced in the 1990s to foster the evolution of the positive youth development (PYD) concept. As discussed by Hamilton (1999), the concept of PYD can be understood in three interrelated but distinct ways: as a developmental process, as a philosophy or approach to youth programming, and as instances of youth programs and organizations focused on fostering healthy or positive development among youth. Geldhof and colleagues focus on the idea of PYD as a developmental process by using a model framed by relational developmental systems ideas; they describe the nature and implications of the considerable research across the adolescent period that has been inspired by this model.

In the next chapter, Jennifer Brown Urban and her colleagues note how developmental systems science extends the conceptual and methodological boundaries of developmental science. They note that the term *developmental systems science* refers to the application of systems science methodologies (e.g., social network analysis, system dynamics, and agent-based modeling) to developmental science questions, particularly those derived from a developmental systems theoretical perspective. The phrase *developmental systems science* deliberately combines *developmental science* with *systems science* and is meant to reflect the joining together of these two fields. *Developmental science* is an approach to the study of human development that emphasizes multidisciplinary and systemic thinking and includes the spectrum from basic to applied forms of inquiry (Lerner, 2006). *Systems science* refers to a family of methodologies that enables the study of complex problems and typically involves modeling and simulation.

This chapter aims to present a compelling rationale for the application of systems science methods in developmental science as well as an introduction to three specific systems science methodologies. This chapter builds on the authors' previous work in this area (Urban, Osgood, & Mabry, 2011) by giving a much richer and more detailed description of the selected systems science methods and by including a brief review of systems science applications in developmental science.

The next section of the *Handbook* presents two chapters that discuss epigenetic development and evolution. Mae-Wan Ho links epigenetics and generative dynamics to explain how development directs evolution. She notes that, whereas the epigenetic approach fully reaffirms the fundamental holistic nature of life and discredits any theory ascribing putative group differences in human attributes to genes (Ho, 2010), it also gives no justification to *simplistic mechanistic* ideas of arbitrary effects arising from use and disuse or the inheritance of acquired characters. It does not lead to any kind of determinism, environmental or genetic. Organisms are, above all, complex, nonlinear dynamical systems (Saunders, 1993), and as such, they have regions of stability and instability that enable them to maintain homeostasis or to adapt to change, or not, as the case may be. The appearance of novelties and of mass extinctions alike in evolutionary history are but two sides of the same coin; we cannot be complacent about the capacity of organisms to adapt to any and all environmental insults that are perpetrated, the most pressing of which is anthropogenic global warming. The dynamics of the developmental process ultimately holds the key to heredity and evolution by determining the sorts of changes that can occur and in its resilience to certain perturbations and susceptibility to others. Our knowledge in this crucial area is urgently required.

What implications are there for evolution? Just as interaction and selection cannot be separated, nor can variation (or mutation) and selection, for the "selective" regimen may itself cause specific epigenetic variations or "directed" mutations. The organism experiences its environment in one continuous nested *process*, adjusting and changing, leaving imprints in its epigenetic system, its genome, as well as on the environment—all of which are passed on to subsequent generations. Thus, *there is no separation between development and evolution*. In that way, the organism actively participates in shaping its own development as well as the evolution of its ecological and social community. We do hold the future in our hands—it is precious; be careful.

In the succeeding chapter Peter T. Saunders discusses dynamical systems, the epigenetic landscape, and punctuated equilibria. He explains that complex nonlinear dynamical systems can have many properties that are not found in linear systems. These properties include multiple steady states, abrupt changes, chaotic behavior, and self-organization. Simply realizing that systems may have these properties can enable us to understand many phenomena without the need to postulate special forces or complicated and implausible scenarios. This chapter illustrates the idea by applying it to biological development and evolution. In particular, a simple explanation is provided for punctuated equilibria.

The next section of the *Handbook* presents two chapters elucidating the links between neural networks and development. In the first of these chapters, Maartje E. J. Raijmakers and colleagues discuss nonlinear epigenetic variance in developmental processes. They point out that the assumption in twin studies—that genotypic and environmental factors reflect the underlying mechanisms causing phenotypic individual differences (e.g., Plomin, DeFries, McClearn, & McGuffin, 2008)—has important problems. First, a limiting feature of behavior–genetic methodology is that the causal interpretation pertains to phenotypic individual differences and not to phenotypes themselves (Dolan & Molenaar, 1995; Lewontin, 1974; Oyama, 1985). Second, the validity of the methodology may be undermined by the limitations of the statistical model employed to carry out the decomposition of phenotypic variance. For instance, genotype–environment interaction, genotypic–environmental covariance, and assortative mating are not taken into account in the standard linear model (but see Plomin et al., 2008). Third, the search for specific genetic and environmental variables may be limited in that an important part of phenotypic variance may be due to nonlinear (epigenetic) processes (Molenaar, Boomsma, & Dolan, 1993; Zuk, Hechter, Sunyaev, & Lander, 2012). Because these effects will appear unsystematic, they are difficult to distinguish from specific environmental effects and measurement error.

Accordingly, the aim of the Raijmakers and colleagues chapter is to study the third limitation: the role of nonlinear epigenetic processes as a source of phenotypic variance. They review the relevant literature and present ample evidence in support of these processes. In addition, they present the results of computer simulations. The implications and consequences of the presence of nonlinear epigenetic variance are particularly interesting in the light of the largely unsuccessful attempts to identify specific, nonshared, environmental influences (e.g., see Turkheimer & Waldron, 2000).

In turn, in the second chapter in this section, Gregor Schöner presents a penetrating discussion of the self-organization metaphor, emphasizing that mere mathematization in the form of, for instance, reaction–diffusion models explaining biological pattern formation is not sufficient to transform this metaphor into productive theory.

He then moves to an equally penetrating discussion of the dynamic systems metaphor, taking Waddington's epigenetic landscape as example. Schöner lists the strengths, but also several important weaknesses, of the dynamic systems metaphor. He then shows that dynamic field theory resolves the weaknesses of the dynamic systems metaphor, thus providing a strong theoretical framework for understanding development. This is illustrated by means of two worked examples, the "*A*-not-*B*" paradigm and the habituation paradigm, both providing impressive examples of how dynamic field theory is applied in concrete situations.

The next section of the *Handbook* focuses on the dynamics of development. Flavio Cunha and James Heckman discuss methods useful for estimating the technology of cognitive and noncognitive skill formation. They treat the linear case and therefore include estimates from linear models of the evolution of cognitive and noncognitive skills. They explore the role of family environments in shaping these skills at different stages of the life cycle. Central to this analysis is identification of the technology of skill formation.

The authors estimate a dynamic factor model to solve the problem of endogeneity of inputs and multiplicity of inputs relative to instruments. They identify the scale of the factors by estimating their effects on adult outcomes. In this fashion, they avoid reliance on test scores and changes in test scores that have no natural metric. Parental investments are generally more effective in raising noncognitive skills, and noncognitive skills promote the formation of cognitive skills—but, in most specifications of their model, cognitive skills do not promote the formation of noncognitive skills. Parental inputs have different effects at different stages of the child's life cycle, with cognitive skills affected more at early ages and noncognitive skills affected more at later ages.

In turn, in the next chapter in this section, Han L. J. van der Maas and colleagues use a complex systems approach to discuss the dynamics of development. They provide three examples of modeling and investigating complex systems. First, they present a new model for general intelligence based on a mathematical model for ecological networks. Second, they discuss ways to study phase transitions in psychological systems. Third, they introduce a completely new approach to collect high-frequency data on children's development, which is a necessity for studying complex systems. Through these three examples, the authors aim is to demonstrate the viability of the complex system approach to the study of human development.

The next chapter in this section, by Kurt W. Fischer and Paul van Geert, discusses the dynamic development of brain and behavior. The authors ask how the growth of neural systems in the brain relates to children's psychological development. They note that the study of neuroscience is moving beyond speculation to discovering how brain and behavior connect—how development of brain functioning relates to actions, thoughts, and emotions. This knowledge provides possibilities for moving beyond global correlations to real breakthroughs in the understanding of developmental processes. Analysis of patterns of growth can illuminate how brain functions and behaviors develop through common developmental mechanisms and produce similar growth curves.

The authors propose that two characteristics are especially important for analyzing and explaining the developmental mechanisms underlying brain–behavior relations. First, many growers are connected, with important variations in the types of connections; growers powerfully influence each other's growth. Second, growers commonly move through periods of rapid change or developmental discontinuity, in which new capacities or forms of activity emerge, creating the transformations of childhood and adolescence. Advances in methods for studying development make it possible to analyze the processes of development of brain and behavior.

In addition, Fischer and van Geert propose a framework for analyzing brain–behavior relations in development based on the hypothesis that major developmental changes involve coordination of brain–behavior components into higher-order control systems, which they call *dynamic skills* (Bullock & Grossberg, 1988; Fischer, 1980; Fischer & Bidell, 2006; Grossberg, 1988; Mascolo & Fischer, 2010). Skills comprise multiple elements, following the principles of dynamic systems (Smith & Thelen, 1993; Stein, Dawson, & Fischer, 2010; van Geert, 1991, 1998). Before coordination, connections of these elements are mostly weak. With development of coordination, connections become strong and shape growth functions. The authors conclude that dynamic systems models portray a wide range of phenomena in approximate terms and thus sketch the kinds of phenomena that these models can explain. This important function lays out the sorts of phenomena that dynamic systems models can elucidate.

Karl M. Newell and Yeou-Teh Liu, in the next chapter, discuss the dynamics of motor learning and development across the life span, emphasizing that the scientific subdomains of motor learning and motor development have largely evolved independently of each other. In contrast, Newell and Liu indicate that the existing theoretical approaches to motor development (e.g., the emergence of new movement forms) and motor learning (e.g., task-relevant changes of existing movement forms) share substantial common ground and therefore have to be integrated. To accomplish this integration, they present the epigenetic landscape model as a viable low-dimensional approximation of the high-dimensional dynamic systems underlying motor learning and development. In particular, they show how continuity and discontinuity, as well as the existence of different timescales associated with motor learning and development, are captured by the epigenetic landscape model. These ideas are illustrated by applications to experimental movement learning data involving two timescales and to the occurrence of phase transitions in movement learning.

The next section of the *Handbook* presents two chapters that treat the dynamics of social interaction. Emilio Ferrer and Joel Steele present differential equations for evaluating theoretical models of dyadic interactions. They illustrate differential equation models (DEMs) as suited to examine the interdependence of dyadic members over time. First, they describe theoretical models developed for dyadic interactions. They then apply differential equations representing such models to daily data on affect from individuals in couples. Third, they evaluate the parameter estimates from each model and compare across the different specifications. Finally, they examine the predictive validity of the models by using their corresponding estimates to predict the couples' relationship quality and status 1 and 2 years later.

In turn, Steven M. Boker and colleagues present a differential equations model for the ovarian hormone cycle. They note that dynamical systems models of behavior and regulation have become increasingly popular due to the promise that within-person mechanisms can be modeled and explained. However, it can be difficult to construct differential equation models of regulatory dynamics that test specific theoretically interesting mechanisms.

Accordingly, the authors use the example of ovarian hormone regulation and develop a model to capture features of observed hormone levels and, as well, link parameters of the model to biological mechanisms. Ovarian hormones regulate the monthly female reproductive cycle and have been implicated to have effects on affective states and eating behavior. The three major hormones in this system are estrogen, progesterone, and lutenizing hormone. These hormones are coupled together as a regulatory system. Estrogen level is associated with the release of lutenizing hormone by the hypothalamus. Lutenizing hormone triggers ovulation and the transformation of the dominant follicle into the corpus luteus, which, in turn, produces progesterone. A differential equations model is developed that is biologically plausible and produces nonlinear cycling similar to that seen in a large, ongoing daily-measure study of ovarian hormones and eating behavior.

The next section presents a nonlinear dynamical model of development. Sy-Miin Chow and colleagues discuss a regime-switching longitudinal model of alcohol lapse–relapse. The authors note that general contemporary linear models assume that continuous changes in the predictor variables result in proportionate amounts of (linear) change in the outcome variable. Empirical evidence from the alcohol treatment literature, however, favors the application of nonlinear dynamics models over the general linear model because of their ability to capture sudden, discontinuous jumps in individuals' drinking tendency.

One example of such nonlinear models is the cusp catastrophe model used by Witkiewitz and Marlatt (2004) to represent the complex interplay between different risk factors in triggering sudden shifts in individuals' tendency to drink. Although the cusp catastrophe model has been promising in capturing some aspects of alcohol use dynamics, current approaches of fitting variations of this model do not address several practical data-analytic problems commonly seen in empirical data, including the presence of incomplete data, measurement and/or process noise, the lagged effects of previous drinking on current alcohol use, heterogeneous timing of lapse–relapse within and across subjects, and the large number of abstainers at any given time—commonly referred to as the "zero inflation" phenomenon.

Accordingly, the authors propose a mixture structural equation model with regime-switching (MSEM-RS) as an alternative approach to account for these data-analytic issues, while retaining some of the key features of the cusp catastrophe model. The proposed model is illustrated using longitudinal drinking data from the COMBINE study (COMBINE Study Research Group, 2003).

The next section of the *Handbook* presents two chapters that discuss nonergodic developmental systems. Wayne F. Velicer and colleagues discuss idiographic applications involving issues of ergodicity and generalizability. The authors note that idiographic methods focus on the time-dependent variation within a single individual or unit (intrasubject variability) in contrast to methods that focus on group-level relationships (intersubject variability). Idiographic methods are widely used in other disciplines, such as engineering, business, and economics, but only recently employed in the behavioral sciences. This method is an alternative to the dominant scientific approach in the behavioral sciences, the nomothetic approach, which focuses on group-level analysis.

Accordingly, the authors present three different examples from behavioral medicine to illustrate both the challenges and rewards of using idiographic methods. These include a nicotine harm reduction study, a study of the patterns of adherence in sleep apnea, and an intervention study that identifies different patterns of arousal in children with autism. The studies illustrate how idiographic methods can address unique and important research questions.

In the second chapter in this section, Peter C. M. Molenaar and John R. Nesselroade discuss new trends in inductive developmental systems theory: ergodicity, idiographic filtering, and alternative specifications of measurement equivalence. The authors note that methodological implications of some aspects of development emphasized by RDST have been considered before. For instance, Sidman (1960) presented an overview of early methodological work addressing the (lack of) relationship between individual and average learning curves, starting with Merrill (1931). Wohlwill (1973) criticized the use of interindividual variation in studying developmental processes and, in its stead, recommended a focus on individual developmental functions.

Accordingly, the authors seek to strengthen and generalize these early approaches. That is, they first consider a general mathematical theory, ergodic theory, which specifies necessary conditions for a valid inductive relational developmental systems model based on fitting subject-specific stochastic dynamic systems models with time-varying parameters to appropriate empirical data. Although ergodic theory was founded more than a century ago, its surprisingly direct relevance to inductive relational developmental systems models was made explicit only recently (Molenaar, 2004). Next, a number of important implications of ergodic theory for inductive relational developmental systems models is elaborated, in particular, how to deal with pervasive subject specificity and change in fitting appropriate dynamic systems models to the data. In this context, the authors consider a new approach inspired by these models to estimate subject-specific heritabilities.

The final section of the *Handbook*, by Phillip K. Wood, is a one-chapter integrative summary of the preceding chapters. He presents the interesting point of view that science in general can be characterized as an inductive developmental system in which different scientific models constitute competing webs of beliefs. Wood emphasizes the central theme of this handbook, namely that empirical tests of developmental systems theory are possible, but require appropriate data and models. He presents an insightful discussion of the epigenetic landscape metaphor that figures in several previous chapters, adding important considerations about its manifold theoretical implications and its use in data analysis. The chapter closes with some noteworthy observations and comments on research inspired by developmental systems theory.

Conclusions

The chapters in this handbook are all aimed at fulfilling the scientific promise of developmental systems theories by coupling such models within inductive methods. Across the chapters in this handbook, authors capitalize on the important ingredients of an inductive methodological approach to developmental systems theories that have become available recently, as documented by Molenaar and Newell (2010). This handbook takes an additional and crucial next step. Across the chapters in this handbook (and as summarized by Wood, in the concluding chapter in this volume), the authors integrate these statistical modeling approaches within developmental systems theory. Together, the contributions of the authors culminate in a new powerful set of methodologies and accompanying statistical modeling approaches to fit developmental systems theoretical models to empirical data.

Given this contribution, our hope is that this handbook provides to current and future developmental scientists an understanding of the use of developmental systems theory and methods in the description, explanation, and optimization of intraindividual changes across life and of interindividual differences in such life-span change. We believe that the chapters offer integrative and authoritative discussions of the theory–method synergies in this cutting-edge framework for understanding human behavior and development. As such, we believe as well that this handbook provides to current doctoral-level researchers and professors and to their students a rich and detailed depiction of the nature of past, contemporary, and likely future scholarship pertinent to theory and method in this area of developmental science.

To the extent that the chapters in this handbook enhance understanding of how to employ theory-predicated methods to enhance understanding of the mutually influential relations between individuals and the multiple levels of their context that constitute the developmental system, we believe that the scholarship in this book will contribute to a new era in the conduct of developmental science—one that captures the complexity of the developmental system and enhances the means to not only describe and explain intraindividual change and interindividual differences in intraindividual change but, as well, provides new means to generate evidence-based actions that optimize the course of health and positive functioning across the life span.

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