A Dynamic Systems Approach to Development

Applications

edited by

Linda B. Smith

and

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A Bradford Book
The MIT Press
Cambridge, Massachusetts
London, England

This book was set in Palatino by Asco Trade Typesetting Ltd., Hong Kong, and was printed and bound in the United States of America.

Library of Congress Cataloging-in-Publication Data

A Dynamic systems approach to development: applications / edited by
Linda B. Smith and Esther Thelen.
p. cm.—(The MIT Press/Bradford Books series in cognitive psychology)
"A Bradford book."
Includes bibliographical references and index.
ISBN 0-262-19333-7
1. Developmental psychology. 2. System theory. I. Smith, Linda B. II. Thelen, Esther. III. Series.
[DNLM: 1. Child Development. 2. Child Psychology. 3. Cognition. 4. Motor Skills. 5. Systems Theory. WS 105 D997]
BF713.5.D96 1993
155'.01'1—dc20
DNLM/DLC
for Library of Congress 92-46558
CIP

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Series Foreword

The series on Cognitive Psychology presents a collection of definitive books on cognition viewed from a psychological perspective. It includes undergraduate and graduate textbooks, major reference works, and research monographs on the cutting edge of psychological knowledge, and on occasion, as the situation warrants, a few edited volumes. Books in the series concern a wide variety of topics in cognition, including perception, attention, imagery, memory, learning, categorization, language, problem solving, thinking, and cognitive development. Although the primary emphasis is on presenting psychological theories and findings, most volumes in the series have an interdisciplinary flavor, attempting to develop important connections between cognitive psychology and the related fields of anthropology, computer science, education, linguistics, neuroscience, and philosophy.

Stephen E. Palmer

Preface

The idea for this book grew from a workshop, "Dynamic Systems in Development," held before the biennial meeting of the Society for Research in Child Development (SRCD) in Kansas City in April 1989, and funded by the National Institute for Child Health and Human Development (NICHHD). Nearly 200 participants attended the two half-day sessions, which included a tutorial in dynamic systems principles, and general and specific applications of these new ideas to developmental phenomena, including perceptual-motor systems, cognition, and social and emotional development. The organizers of the workshop (Thelen, Smith, Bertenthal, and Fogel) were surprised and pleased at the widespread interest shown by scholars from many different countries, at different levels of experience, from graduate students to senior people, and from the wide variety of interest areas in the SRCD, including both basic and applied researchers. The enthusiasm of the scholarly community for these new approaches convinced us that a collection of papers from the workshop, plus others we invited, would find a large and receptive audience. Thelen, Smith, Kelso, and Bertenthal also presented a day-long version of the workshop in June 1989 to the Human Development and Aging Study Section 1 of the NICHHD, at the invitation of and funded by the NICHHD.

Why the interest in dynamic systems? Certainly, one reason is that dynamic systems are "in the air." There has been a spate of accessible and engaging books, a *NOVA* program, and many articles in the popular scientific journals about chaos theory, fractals, and the wondrous properties of self-organizing systems. There are now mathematical dynamicists at work not only in "think tanks" such as Los Alamos but also in medical schools, biology laboratories, and social science departments. Although it may be too early to tell whether the study of complex systems represents a real paradigm shift or an insignificant blip on the scientific radar screen, it is true that these ideas have caught the imaginations of many, scientists and laypersons alike. There is also no question that although the principled study of complexity has heretofore been the province of a rather eccentric fringe, the availability of massive computing resources has brought this endeavor into the mainstream and even onto the frontier.

The Kansas City meeting demonstrated that developmentalists, perhaps uniquely among social scientists, are unusually interested in, and receptive to, dynamic approaches. There are several reasons why this may be so. First, there has been a long tradition of so-called systems approaches in developmental theory, from Werner, Waddington, von Bertalanffy, Weiss, through Piaget, Lerner, Sameroff, Gottlieb, and others. The systems tradition is holistic, antimechanistic, probabilistic rather than deterministic, and emphasizes self-organization and self-stabilization. This "organic" metaphor pervades our theory, if not our practice (see Oyama, 1985; Thelen, 1989). So the intellectual ground has been well spaded by nearly a century's work.

But equally important, we believe, is the unusually wide gap between the large and important body of empirical work in human development, and a synthetic theory or theories to explain the extant data. Piaget filled that gap for many years for mainstream perceptual-motor, cognitive, and to a lesser degree, social and emotional development. Piagetians no longer dominate the scene; consequently much, and probably most, developmental research is now atheoretical, and in some cases, even antitheoretical. But the quest for unifying principles to explain what we know and to guide our future work remains. Can development be so domain-specific that little or nothing can be said about general processes? Are there higher principles of stability and change, emergence and regression, of patterns over time, that transcend the particular experimental manifestations? In short, without Piaget, can there be a relation between early sensorimotor behavior and later cognition?

In seeking theory, developmentalists are first and foremost eager for an explanation of *change*, and particularly how new forms of behavior can arise from precursors that do not themselves contain that form. Developmental psychology, like other branches of experimental psychology, has borrowed heavily from physical sciences before—information-processing is the notable example—but these metaphors have fallen short because they do not address this fundamental question. Dynamic systems are systems that change over time and that can autonomously generate complexity and form. Even on the surface, the metaphor fits.

And finally, we believe that developmentalists will be receptive to dynamic systems because we come face to face with complexity, nonlinearity, and context-dependency every day. When dealing primarily with infants and children—or with aging, handicapped, or disadvantaged populations—the real complexity of subjects' lives cannot be avoided through clever experimental design. Such populations cannot or will not memorize lists of letters or perform constrained and simplified tasks. They bring their family situations, physiologic and emotional states, temperaments, and abilities into the laboratory or observational setting. Empirical tests of theoretical models of abstract human performance are possible with healthy, young, well-educated, cooperative adults. Theory becomes more constrained, however, when it must account for the richness, variability, flexibility, and independence of subjects who are not being given course credit for participating.

As the chapters in this book will attest, dynamic systems cannot yet be claimed as a fully articulated and unified theory of development, such as, for example, that from the singular genius of Piaget. At its current state of development, dynamic systems is being used by different researchers and theorists for many different levels of analysis, for behavior ranging from the physiologic to the social, and for describing change over time scales from seconds to years. We see this diversity, however, not as a failing of the approach, but indeed as its real strength. Because the many local deviations from Piaget's stage descriptions brought the whole of Piagetian structuralism into question, we are now alert to the pitfalls of explaining too much by single, overarching organization. It seems to us that the future of developmental theory will lie—as in dynamic systems—with very general principles of process and change, applicable in many domains, over many levels and time scales, but also allowing the multiple local details to emerge from the necessary empirical work.

The chapters in this book are among the first attempts to bridge the general principles with applications to developmental issues that span these domains, levels, and time scales. Readers may find the diversity daunting at first, perhaps even undisciplined. In nearly all the chapters, dynamic principles have been used post hoc to explain or formalize data collected previously by the authors and others, and, by implication, for which other theoretical approaches have been less than satisfactory. We view this enterprise as the necessary first test of dynamic ideas: Can we make more sense of our existing data with dynamic assumptions than with other competing frameworks? Only when the community at large, and individual researchers in particular find these ideas enlightening and even comfortable, will the more critical connections be made between theory and experimentation in the form of studies explicitly generated by and interpreted within a dynamic framework. As readers will note from the chapters in this book, these connections have been and are being made most clearly by researchers in the field of perceptual-motor development, for both historical and methodologic reasons.

We hope that readers will discern the commonly shared assumptions among the diversity of subjects and techniques presented in these chapters. Although we point these out more specifically in our introductions to each section, we provide a brief overview here. Central to all dynamic formulations is the assumption that behavior and its change over time are the result of emergent, rather than prescribed processes. Regularity and pattern, be it the temporal organization of movement over several time scales (see Robertson, Cohen, and Mayer-Kress; Goldfield, Roberton; Clark, Truly, and Phillips; and Wolff), the acquisition of new words (van Geert, Tucker), or the patterns of social interaction over hours and days (Eckerman, Newtson), does not require the preexistence of a program, schema, code, clock, or otherwise iconic representation of the form. Emergent form is possible, according to dynamic principles, because the systems involved are complex, and because they utilize energy in a particular way to maintain that complexity. Complexity means that many, often heterogeneous components cooperate (or compete—van Geert) to produce the behavioral outcome. The components operate at many levels of organization and at many, often different, time scales (e.g., Goldfield, Eckerman). The behavior—a condensation of these many possible degrees of freedom—shows pattern in time and space that is not contained in any of the components alone. Such self-organization is possible because dynamic systems, like all living organisms, are *open* systems. They freely exchange energy with their surrounds and indeed, in thermodynamic terms, become local energy sinks, absorbing energy and using it to maintain their order in the face of universal energy dissipation.

The implications of seriously viewing developing organisms as dynamic, open, contingent systems are profound. Because the state of the system depends on the organism within its total context, there can be no logical distinction made between the organism and the environment as the *cause* of behavior and its change. Causality, as a linear chain of precedent and antecedent events, cannot be singularly assigned to any agency within or surrounding the organism. Rather, the organism's position in the state space—the space defined by all possible parameters of the cooperating components—is determined by the *collective* activity of those components. The system's stability, and thus its vulnerability to change, results from the relative dynamic interactions of the components. (In their chapters, both Kelso, Ding, and Schöner, and van

Geert show formally how complex trajectories can evolve over time from the coupling of multiple components.) In terms of traditional developmental issues, this inseparability means that the distinction between the "biological" and the "environmental," including the cultural and social context, is not tenable, nor is partitioning behavior into these dichotomous categories.

A second challenge to traditional conceptualizations is the serious consideration of nonlinearity. Systems composed of multiple, cooperative components do not occupy homogeneous regions of their possible state spaces. Rather, as they evolve over time, they may shift in a discontinuous manner from one qualitative mode to another. Phase shifts may occur even when the two modes are separated by values on a particular parameter so small as to be virtually undetectable by our conventional measurements. This means that within the deterministic dynamic regime of the system as a whole, there may be considerable local unpredictability that is not resolved by improving the measurements. Thus, the individual course of a developmental trajectory may never be fully knowable beforehand, even though the global outcome can be quite confidently predicted.

Finally, in contrast to traditional views where variability from a mean standard of performance is considered as noise in the system, dynamic approaches give variability important theoretical status. This has two important consequences: First, the use of group averages and conventional inferential statistics may be appropriate only at the first, most global level of analysis. Understanding process must involve the use of individual developmental data, collected longitudinally. Several chapters in this book make this point; and it is noteworthy that formal dynamic treatments (Roberton, Robertson et al., Clark et al., and van Geert) must rely on individual data for modeling or as exemplars. Second, as Kelso and his colleagues point out, dynamic approaches predict increased variability as an index of patterns in transition from one form to a new form. The notion that variability is a manifestation of transitions is not a new idea for developmentalists, but has yet to be widely exploited as an experimental strategy (cf. Siegler and Jenkins, 1989; Thelen and Ulrich, 1991).

We have divided the volume into two parts. We introduce part I with a primer on dynamic pattern formation by Kelso and his colleagues. This chapter presents dynamic principles in generic form applicable to questions of pattern formation in any biological organism over many time scales. The remainder of the first section contains chapters whose focus is primarily on the motor performance of developing infants and children. Because, among all the social and behavioral sciences, dynamic approaches have been most well-formulated for motor behavior, it is not surprising that they have also been adopted most widely for the study of motor ontogeny. In part II, the authors cast their nets more broadly into various domains of inquiry, including perception and its relation to action, infant state, cognition and language, and behavior within the largest social and ecologic spheres. Finally, Richard Aslin provides a concluding commentary and critique.

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Acknowledgments

One of the joys of the scientific endeavor is the community of minds meeting on mutual discovery. This book is both the culmination and, we hope, the beginning of such meeting. Many individuals and institutions have helped bring this collection together.

First, we would like to thank our co-organizers of the 1989 workshop, Bennett Bertenthal and Alan Fogel, the participants in that workshop, and the contributors to the book for their willingness to contribute to these new ideas. Some of the participants were already converted to dynamics, others took up the gauntlet cautiously, and still others remain interested, but skeptical. It has been enormously enriching to partake of the dialogue.

The National Institute of Child Health and Human Development, and especially Norman Krasnegor and Teresa Leviton, supported the 1989 conference and the subsequent one-day study-section workshop. These meetings, under the auspices of the federal establishment, gave us both the legitimacy to pursue these ideas and the wherewithall to get together to create the necessary critical mass. We appreciate their support.

Our colleagues and friends at Indiana University have provided the perfect balance of challenge and support for us in our explorations of new dynamic theory and experiment. Of special importance is the Dynamics Group of the IU Cognitive Science Program. The Dynamics Group has been meeting since 1987, and we would especially like to thank Robert Port, Timothy van Gelder, Beverly Ulrich, James Townsend, Geoffrey Bingham, and David Jones for consistently stimulating insights and important collegiality. The Indiana University Dean of Faculties Multidisciplinary Ventures Fund has provided us with timely grants to maintain this group. We would like to also acknowledge the leadership of Richard Shiffrin, who has made IU Cognitive Science so open to new ideas.

We are equally indebted to our colleagues in developmental studies, who have made Indiana a place where ideas are important and where we share a commitment to studying developmental process. These colleagues include Jeffrey Alberts, Susan Jones, Meredith West, Sheila Walker, Steven Barlow, Beverly Ulrich, and Alexandra Quittner. These people have contributed greatly to our inquiry and growth. In the same breath, we also thank our students, postdoctoral associates, and laboratory colleagues who have been the best sounding boards for these new ideas. These include Karen Adolph, Daniela Corbetta, Lisa Gershkoff-Stowe, Steven Goldinger, Dexter Gormley, Diana Heise, Jodi Jensen, Kathi Kamm, Donald Katz, Juergen Konczak, Theresa Mitchell, Michael Muchisky, Brigette Oliver, Michael Schoeny, Maria Sera, Gregory Smith, John Spencer, Beatrix Vereijken. We subjected many more students in our graduate and undergraduate classes to "test runs" of dynamic ideas and chapters, and we thank them all for their encouragement and comments.

Margaret-Jean Intons-Peterson, Chair of the Indiana Psychology Department, has been consistently supportive. The IU Department has long been known for its collegial atmosphere, and Peggy has nutured it particularly well. Amber Cox deserves special gratitude for her work on some of the figures in this book, as does Karen Jukes for tackling difficult typing with skill and enthusiasm. Mary Buuck along with Amber Cox merit medals for outstanding service in preparing the author index and overseeing corrections to the page proofs. We also thank Donald Katz, John Spencer, and Theresa Treat for preparing the subject index with such intelligence and good humor.

Our research and writing has been supported by several grants and agencies, including research support from NIH (RO1 HD 22830 to E. T. and RO1 HD 28675 to L. B. S.), a Research Career Development Award from the NIMH to E. T., and several internal grants from Indian University. Specific sources of support for the individual chapters are acknowledged in the chapters.

Our families have been a constant source of strength. Our husbands, Maurice Smith and David Thelen, and our children, Evann and Gordon Smith and Jennifer and Jeremy Thelen, kept us sane. For this, and much more, we thank them.

L. B. S.
E. T.

Contents

PART I

From the Dynamics of Motor Skill to the Dynamics of Development

We begin this book with a tutorial on the general principles of dynamic systems by Kelso, Ding, and Schöner. (This is an extended version of the tutorial presented by Scott Kelso at the 1989 Society for Research in Child Development [SRCD] workshop which inspired this collection.) This chapter is an appropriate beginning for several reasons. First, Kelso, and his colleagues present an overview of the concepts and techniques of dynamic principles in a abstract, rigorous, but still qualitative manner. There is a sizable gap in the literature between the readable and popular accounts of dynamic systems such as Gleick's *Chaos* and the more formal, but heavily mathematical treatments (e.g., Haken, 1977) which may be inaccessible to many developmentalists. We hope that chapter 1 strikes a happy balance.

Our second reason for welcoming the contribution by Kelso and his colleagues is to emphasize the wide generality of dynamic principles. The authors wrote this tutorial originally for an edited volume dealing with biological organization in embryology, evolution, morphology, neurobiology, and physiology (Baskin and Mittenthal, 1992). As they state in their introductory paragraphs, many fields in the biological sciences deal with the same fundamental processes: the emergence of patterns in structure or behavior, and the stability and change of those patterns. Certainly this is the foremost enterprise of developmental psychologists. Because the concepts of dynamics are content-free and address these questions at an abstract level, they are applicable to behavioral development as well as to other biological processes at micro- and macro-levels. (A number of authors have commented earlier on the relevance of contemporary nonlinear dynamics to development, e.g., Brent, 1978; Kitchener, 1982; Kugler, Kelso, and Turvey, 1982; Waddington, 1977). Explicit applications of dynamic principles to development are made by many contributors to this book and have been made elsewhere (e.g., Thelen, 1989; Thelen, Kelso, and Fogel, 1987; Thelen and Smith, in press; Thelen and Ulrich, 1991). For example, the concept of behavioral patterns as *attractors* which change over time is central to all the chapters, as is the notion of *coupled* processes. In addition Bertenthal and Pinto in chapter 8, Clark, Truly, and Phillips (chapter 3), and Roberton (chapter 4) use phase plane depictions of motor actions, Robertson, Cohen, and Mayer-Kress (chapter 5) find evidence of a chaotic attractor in the cyclic activity of young infants, and van Geert (chapter 10) models cognitive processes using the logistic equation.

The very generality of dynamic concepts as a basis for new developmental theory has both strengths and weaknesses. Where dynamic system approaches are most powerful, we believe, is in providing a set of assumptions about how behavior is organized and how it changes, and a strategy to empirically unlock those processes, that applies to every domain and level from the neurobiological to the actions of social groups. No other developmental theory offers such sweeping generality. Even more potent is that these principles, as attested to by Kelso and his colleagues, put the processes of human development into the wider universe of emerging complexity seen in all biological, and many physical, systems.

The lack of content will be seen by many as a weakness of the approach. Dynamic systems has nothing to say about the particular collective variables, the parameters of the state space of the developing organisms, the nature of the coupled components, or of the internal or external mechanisms that act as the proximal agents of change. These must all be discovered, within the assumptions of the approach, by painstaking empirical study. Thus, dynamic systems is a theory of development in the most abstract sense: it is not a theory of motor development, or of cognitive development, or of social development without the complement of data to test and illustrate the assumptions. Hopefully, the chapters that follow will make some of these connections. Thus, we ask readers to approach the Kelso et al. chapter in the spirit of asking how these general principles can help recast questions in their own areas of interest.

We would, in addition, like to call attention to a concept introduced by Kelso et al. that is of special importance to developmentalists: that of *intermittent dynamics*. A system exhibiting intermittent dynamics is one that "lives" near a fixed point, but not actually in it. Many biological systems appear to display such dynamic regimes. Why are intermittent dynamics important? A central question for developmentalists is how behavior can show both stability and flexibility, especially the flexibility to move into new solutions—the essence of developmental change. When behavior is seen as controlled by "schemas" or programs in the brain as fixed symbols or representations, it is a major theoretical challenge to find mechanisms by which the old schemas dissolve to be replaced by new forms. If, however, behavior is seen as quasistable, dynamically "visiting" a preferred configuration, but not rigidly captured by that configuration, the origins of new cooperative relations among the components are apparent. Developmentalists deal every day with systems displaying these dynamics—behaviors that are sort of stable, but easily perturbed by even minor procedural or contextual changes, or by the infant's or child's particular momentary state. In our traditional paradigms, we call these dynamics variability or *noise*, and they confound our attempts to find a main effect. But this dynamic lack of fixed responses, of the system moving and being easily bumped, is, according to dynamic principles, a theoretical necessity for phase shifts. Conceptualizing this inherent variability not as messiness but as the essential *source of change* can profoundly reorient both the theoretical vision and the operational strategy to developmental study.

Readers will note that this book is top-heavy with chapters about early motor and perceptual-motor development. There are two reasons why investigators in this area have been among the first to find dynamic systems approaches compatible and useful. The primary reason is historical and relates to the rise in the last decade of dynamic approaches to adult motor behavior. A few decades ago, researchers studying the control and coordination of adult movement with the prevailing models faced a theoretical roadblock. Motor control was believed to be of two types, so-called closed-loop or open-loop. Closed-loop theorists imagined the system to be a feedback loop; as movements are produced, an error signal is fed back to a central processing station, continuously compared with the ideal goal of the movement, and correction signals generated centrally to keep the movements on course. Open-loop theorists, in contrast, believed that a central command structure or schema specified a set of instruc-