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Rulers, models, and nonlinear dynamics: Measurement and method in developmental research

Abstract

Nonlinear dynamic systems provide a powerful new framework for analyzing development and other forms of change, but two research approaches have limited research to date. Data-driven approaches have focused on describing specific phenomena, especially actions, and have used dynamic concepts mostly as loose metaphors instead of building explicit models. Model-driven approaches have focused on the rich hypotheses in developmental theory to generate and explore formal models of change processes, mostly involving cognition and language. They have neglected the need for careful research to measure the growth patterns to be explained. The difficulties of doing dynamic research on cognitive, language, and socioemotional development stem in large part from the absence of well constructed scales for assessing behaviors other than actions. Construction of such scales is facilitated by combining scores on carefully analyzed tasks and by assessing scale properties across different assessment conditions, so as to separate growth properties from scale anomalies. With good scales, models and data can be used in dynamic interaction to generate powerful explanations of development, as illustrated by models of hierarchical growth and predator-prey relations in cognitive and brain development.

Introduction

There is a new wave of research and theory on development that promises enormous improvements in the quality of scientific understanding and explanation of how people grow, learn, and change. The approach behind the wave is nonlinear dynamics, which brings with it new concepts, methods, and theoretical tools for explaining more fully the nature of development and other forms of change. This book represents effectively the range and scope of the new, exciting work.

When a new approach bursts onto the scene, it often seems to grow of its own accord, surging forward in specific arenas where new research is easier and moving less energetically in arenas where research is stickier. If nonlinear dynamics is to grow to its full potential in explaining development, scholars need to consider not only the arenas where dynamic research is booming but also those where it is struggling or less mature. The publication of this book on the scope of dynamic developmental research provides a good occasion for assessing the strengths and weaknesses of dynamic work to date. Stepping back to assess the state of the art can help to shape future work, potentially making it richer, more compelling, and more comprehensive, catalyzing the field to take the new approach to its full potential.

Analysis begins with the simple question, What do we want to explain about development and other kinds of change? Children and even adults develop dramatically over many years, providing a natural source of rich observations. Among all those developments, what kinds of phenomena have researchers focused on, and how well do those choices capture the range of changes that require explanation?

Research on dynamics of development falls primarily into two types, that driven by data on patterns of change and that driven by models of processes of change. Both data-driven research and model-driven research have produced important new knowledge about development. The division of research into these two primary types, however, has also seriously restricted the scope of phenomena under study, producing large gaps in the field. Moving beyond these gaps requires working simultaneously and reciprocally with both data and models in approximately equal parts. It also requires deep analysis of issues of scaling in measures of change — a topic that is vastly neglected in research on development. By bringing together data, models, and scaling, researchers can move beyond the initial, powerful but spotty successes of nonlinear dynamics in explaining development. Perhaps we may even succeed in building a powerful new kind of explanation of change that will transform the field, shifting psychology and related disciplines from the study of dichotomies and other oversimplifications to the description and explanation of some of the richness of human behavior.

Constructive Dynamics: Phenomena To Be Explained

The promise of nonlinear dynamics is to explain the combination of many influences or components to form human activity, especially processes of development and change in human activity. Virtually all researchers and scholars who use concepts of nonlinear dynamics share an approach that we call *constructive dynamics*, which begins with two central assumptions: First, many influences come together to form the emergent properties of human action and thought. Second, a person is a self-organizing system who regulates these combinations based on feedback from both the immediate world in which the activities are embedded and his or her previous experiences and activities, especially those immediately preceding the activity to be explained. In other words, a person *constructs activities*, regulating the combination of influences that produce those activities through dynamic processes that centrally

involve feedback from the immediate world and prior experience (e.g., Fischer & Bidell, 1997; Gottlieb, 1992; Lerner, 1991).

Constructive dynamics is also constructive in another sense. For many decades concepts from systems theory have been used to criticize work in psychology and related behavioral sciences by pointing out the narrowness and one dimensionality of most social-scientific explanations (Bronfenbrenner, 1979; Sameroff, 1975; Thelen & Fogel, 1989; von Bertalanffy, 1968). However, with classical systems theory few researchers were able to move beyond the criticism to use the concepts constructively to produce better research and theory. In contrast, the new constructive dynamics is generating novel research and theory in many arenas.

The scope of phenomena to be explained by developmental constructive dynamics is vast. The large changes of ontogenesis extend from before birth well into adulthood, if not old age, and include the many aspects of human behavior: action, understanding, thinking, problem-solving, emotion, even consciousness. It is no small task to explain the development of this range of phenomena.

The study of development is blessed with several characteristics that facilitate the application of nonlinear dynamic concepts. First, development involves many instances of systematic change, thus providing orderly phenomena for study. Second, the field of human development has a history of richness in theory, providing fertile sources for ideas about developmental processes that can be used in modeling and research. Witness the work of Freud (1923/1961), Piaget (1983), Vygotsky (1978), and Werner (1948), four of the most influential classical scholars of development. Building upon richly systematic patterns of change and extensive theoretical concepts, researchers may be able to build strong nonlinear dynamic explanations more quickly than in other arenas.

To date, however, most nonlinear dynamic research has focused on analyzing actions, both in development and in human behavior more broadly. Movements of limbs, sense organs (especially eyes), and bodies in space have been the focus of a large proportion of research, as evidenced in the chapters in this book. Much of this research, especially in the study of development, has been data-driven, emphasizing description of specific phenomena involving actions more than construction of models.

Data-Driven Dynamic Research

Data-driven research centers on identifying and describing specific developmental phenomena that have dynamic properties, such as nonlinear growth and shifting developmental patterns from multiple influences, especially as they apply to actions. Esther Thelen has been an eminent practitioner of this kind of research, and she articulates and defends it in a number of publications, including two books with Linda Smith (Smith & Thelen, 1993; Thelen & Smith, 1994).

In one important series of studies, for example, Thelen and her colleagues demonstrated that a developmental pattern that scholars have attributed to changes in the central nervous system is produced by 'peripheral' changes in the body that had gone unnoticed. The stepping reflex of early infancy disappears because babies' legs grow

large in mass and the mass interferes with leg motion and therefore stepping. When an infant who has 'lost' the stepping reflex stands in water, the buoyancy of the water supports the legs and produces a return of the stepping pattern (Thelen & Fisher, 1982). Similarly, when a 7-month-old infant is supported on a treadmill, the movement of the treadmill produces the return of the stepping pattern (Thelen & Ulrich, 1991). With this research, Thelen and her colleagues demonstrated that multiple influences shape growth, not only changes in cognition and brain.

Beyond Demonstrations to Explanations

Most recent work on dynamics of development has involved such demonstrations of complex or counterintuitive phenomena — complex growth curves, appearances and disappearance of behaviors from unexpected influences, interactions among diverse factors affecting development (Fogel, 1993; Goldfield, 1995; Lewis, 1995; Smith & Thelen, 1993). Dynamic concepts such as attractor, self-organization, and catastrophe have become common parlance in the field, proffered as new metaphors for explaining complex developmental patterns. As a result of such work, more and more people have sat up and taken notice of nonlinear dynamics. However, demonstrations and new global metaphors are not enough. As elegant as such demonstrations are, they only begin the process of building dynamic explanations.

If nonlinear dynamics is to reach its potential in the study of development, we must move from demonstrations to explanations. To be constructive, researchers must build dynamic explanations of developmental patterns, not only showing that multiple factors are relevant to a developing activity, such as stepping, but building explicit models that show how various factors come together to produce the developmental pathways for that activity (stepping and walking). Fortunately, a number of the contributors to this volume have moved to build rigorous dynamic explanations for the demonstrations that they have uncovered, with the goal of combining mathematical models of action processes with careful measurement. To produce real explanations of development of action systems, dynamic analysis requires the combination of explicit models with careful measurement.

Why So Much Research on Actions?

In research on dynamic development, actions have been the preponderant focus of research, especially actions in infants. The extent of this emphasis is evident in this book, where most of the research involves actions in infants. In contrast, most traditional (nondynamic) developmental research has centered on cognitive or socioemotional development, not actions. Witness the selection of chapters in widely read compendia, such as the *Handbook of Child Psychology* (Damon, 1997), where a whole volume is dedicated to cognitive development, another volume to social development, but only a few scattered chapters emphasize actions. Why is research on action so popular among researchers interested in nonlinear dynamics in contrast to the rest of developmental science?

When developmental patterns are assumed to be complex (nonlinear), a requirement comes to the foreground that is often neglected in traditional research — finely graded measurement. Describing developmental patterns requires the use of powerful rulers to assess behavior. For researchers to detect ups and downs instead of simple linear patterns, a coarse ruler simply will not do.

Unlike most developmental domains, action can be studied with a ready-made ruler of exceptional power — the Cartesian coordinate system for describing locations in space. This system for measuring location in terms of three axes (dimensions) provides researchers with effective rulers for measuring actions with straightforward precision. Movements can be localized in space and assigned exact numbers in three dimensions, which provide a powerful tool for assessing patterns of action and how they change. No such measurement tools are available for most other kinds of behaviors. The availability of this powerful measurement tool promotes the study of actions by dynamically oriented researchers because it allows them to describe precisely the complex patterns of movement and development that they are searching for.

As important as actions are, people do not simply act. They also talk, think, solve problems, interact with each other, express emotions. Most of the extensive research and rich theory about development involves these other domains, not actions. Dynamical research on development needs to engage these other domains seriously, building on the strengths of past research and theory and constructing tools for careful measurement of cognitive and socioemotional development as well as actions.

Model-Driven Dynamic Research

Model-driven research differs from data-driven research in a number of ways. Most obviously, it focuses on explicating specific models of growth and development in mathematical terms and testing those models to determine whether they produce the developmental properties that theorists have claimed for them. In addition, its content involves cognitive and language development more than actions, perhaps because the dominant developmental theories (Piaget, Werner, Vygotsky) have emphasized those domains. Among the most distinguished practitioners of this work have been Paul van Geert (1991) and Han van der Maas and Peter Molenaar (1992). The model-driven research has explicated developmental processes with mathematical rigor, giving new life and power to concepts such as equilibration and stage.

Growers, Catastrophes, and Beyond

One of the strengths of model-driven research is that it makes theories of developmental process explicit, tying down fuzzy concepts and metaphors so that they become subject to research. One kind of research that becomes possible is what van Geert (1996) calls 'experimental theoretical psychology.' By testing out different

parameter values for a model, one can determine how a specific kind of process produces variations in growth patterns.

Fischer and Kennedy (1997) built a model for the development of hierarchical skills called growers, in which later skills are based on earlier ones; most skills in the Piagetian tradition and most skills taught in schools are hierarchical. The investigators experimented with the model to determine the circumstances under which stage-like discontinuities (sudden jumps and drops) occurred, finding that stages were prominent and robust under some conditions and nonexistent under others, with many variations in between. Stage-like change was prominent when two conditions were present: Growth rates were high, and higher-level growers supported lower-level growers more than they competed with them. Stage-like change was uncommon (development was relatively smooth and continuous) when growth rates or between-level support were low. The range of growth patterns in the model fit empirical findings showing both stage-like and continuous growth for the same skills in the same people, depending on assessment conditions.

In another example of the empirical power of building explicit models of theory, van Geert (1998, in press) constructed a model of the process of equilibration that Piaget ascribed to development. Experimenting with the properties of growth under different parameter values, van Geert found results that seem to explain how person-environment relations produce distinctive growth patterns. With tight feedback between person and environment, development is mostly smooth and continuous, as when a teacher or parent carefully monitors a child's behavior and continually targets input to be slightly beyond the child's current level of skill. In contrast, with looser feedback between person and environment — the situation that Piaget hypothesized to be most common — development of skills shows a series of stage-like jumps similar to Piaget's developmental stages.

Another kind of model-driven research is emphasized in this book, the use of catastrophe theory to analyze development. Van der Maas and Molenaar (1992) identified a series of nine empirical flags that together indicate that a developmental change fits the mathematical model of a catastrophe, especially a cusp catastrophe. A catastrophic change is a strong kind of discontinuity, more than just a jump or drop but a jump to a different kind of emergent form. Many of the chapters in this volume as well as research elsewhere have used these empirical flags to search for catastrophic developmental transitions. For example, van der Maas studied children's solving of Piagetian conservation tasks repeatedly over a number of months in a school setting (van der Maas & Molenaar, 1995). He then examined each child's growth curve to see whether children showed catastrophe-like jumps in performance as they acquired concepts of conservation of amount. Some of the children showed evidence of catastrophic (or at least discontinuous) growth, and others did not. Such variability in growth patterns across children should be the norm, according to nonlinear dynamic analysis.

Model-driven research of this kind provides the possibility of comparing different kinds of developmental-process models. Catastrophe theory provides one model of development, and others include simple logistic growth, such as that postulated by Rasch (1966), more complex hierarchical logistic models that may or may not have

the properties of catastrophes (Fischer & Kennedy, 1997), linear growth, and many other possibilities.

Collecting Relevant Data for Testing and Comparing Models

A necessity in dynamic research on cognitive and emotional development is the creation of suitable rulers for sensitively measuring change. Many cognitive-developmental researchers do not deal effectively with the need for a sensitive ruler to describe the shape of development of a skill. A task that is scored pass-file, for example, cannot be used to test for catastrophes in development or any other kind of dynamic growth, because the scores can be only 0 and 1. It is also problematic to use one 0/1 task for each stage and combine them to form a scale, because each task will produce a jump from 0 to 1 because of its scale properties, independent of the true underlying pattern for skill development. The growth curve will thus appear to show stage-like jumps in performance from stage to stage, but they will arise entirely from the measurement properties of the ruler, not from the nature of the developing behaviors. Adding scoring of a transition step for each task can make the situation even worse, because the intervals between steps (0 fail, 1 transition, 2 pass) are typically not equal. Consequently, further misleading anomalies will be introduced into the growth curve (Rose & Fischer, 1998).

Despite classical calls for careful research on the nature of effective developmental rulers by Wohlwill (1973), Flavell (1972), McCall (1983), and others, few developmental researchers have attended to this important issue for cognitive or emotional development. Happily, some researchers seem to be starting to seriously consider how to build effective developmental scales (Bond, 1995; Case, Okamoto, with Griffin, McKeough, Bleiker, Henderson, et al., 1996; Smith & Sera, 1992). For most important psychological characteristics, there is no easy solution, but two strategies do provide a good start (Fischer, Pipp, & Bullock, 1984).

With the multiple-task method, used in many investigations, including van der Maas's (1995) study of conservation and many psychometrically oriented studies, a set of similar tasks that are cognitively or emotionally equivalent are grouped together, such as eight tasks of approximately equal complexity each assessing the arithmetic operation of addition. These eight tasks can then be used to form an eight-point scale. However, the assumption of equivalence of the tasks is important, and it should be assessed empirically. Combination of tasks that are not approximately equivalent creates an anomalous scale, with properties that can confuse analysis more than illuminating it.

Second, with the strong-scalogram method, a researcher can build a set of tasks that are ordered in terms of complexity (or some other psychological dimension) but are otherwise approximately equivalent.. These tasks can be used to form a Guttman scale, which at its best can provide a highly sensitive ruler for analyzing developmental patterns. As with the multiple-task method, however, empirical assessment of scale properties is essential, so that it is possible to test the expected ordering of tasks and determine other scale properties. Assessment of the relative distance between steps or tasks is especially useful (Fischer, Knight, & Van Parys, 1993).

For both methods, combining the tasks to form a scale is only the beginning of devising a good ruler. Empirical tests of assumptions of equivalence and ordering are essential before a scale can be confidently used to assess developmental patterns and test findings against growth models.

Model-driven research has clearly made important contributions to dynamic analysis of development. To bring the work to its full potential, however, researchers need to move in three main directions, two of which are strongly evident in this volume. First, they need to bring their models more closely into contact with data, not merely demonstrating that a model produces growth curves that are globally similar to empirical ones but carefully testing the model against the data. Only when a model can be tested against rich growth data will it be possible to move firmly beyond well articulated metaphor and construct a true working theory of development of some behavior.

Second, researchers need to work with multiple models and compare them to each other. As exciting and potentially powerful as catastrophe theory is, for example, it is only one kind of model. Van der Maas and Molenaar (1992) hypothesize that important developmental changes all involve catastrophes, but that hypothesis can only be tested when other kinds of dynamic models are also tested, so that comparisons can be made of the effectiveness and usefulness of different models.

Third, researchers need to focus on constructing effective rulers for measuring important characteristics of cognition, language, and emotion. This direction is the one that is most lacking in the field and in this volume, except for research using Cartesian measurement of actions. Only with sensitive scales of important behaviors beyond actions can research on dynamic development become mature and convincing.

Separating Distortion from Nonlinear Change in Developmental Scales

How can sensitive scales be built in domains where ready-made scales are not available? Beginning with tools such as the multiple-task and scalogram methods, researchers can readily build scales and test their properties. Researchers can empirically separate nonlinear growth properties from scale distortions and thus construct effective scales for assessing cognitive and socioemotional development. A straightforward method for separating growth properties from scale distortions is available, but it has been used only rarely in developmental research.

To test the properties of a scale, a researcher should use the scale to assess development under two or more assessment conditions that are likely to produce distinctive growth patterns. As a rule of thumb, differences in growth rate are especially likely to produce distinctive patterns. Comparison of scale properties across conditions then provides a way of separating scale properties from growth-curve properties (Fischer & Kennedy, 1997).

One example of this kind of assessment involves the development of conceptions of the self in important relationships, which is predicted to show hierarchical development analogous to development of more traditional cognitive skills (Fischer, 1980; Harter & Monsour, 1992). The Self-in-Relationships Interview

assesses adolescents' conceptions and feelings about themselves in important relationships, such as with their mother, father, best friend, or teacher. Adolescents generate their own categories for these relationships and explain them to an interviewer. Two different assessment conditions are used. (1) In a low support assessment, participants describe themselves in the relationships without any visual aids or structured questions from the interviewer. This procedure is similar to traditional assessment conditions in much research on self-concepts. (2) In a high support assessment, participants write down their descriptions on small pieces of paper, which they arrange in a diagram like that in Figure 1. The interviewer asks structured questions to help adolescents create their own self-in-relationships portrait and to evoke explanations of key components of the portrait. Each participant also indicates the emotional valence of each description (+ or -), the grouping of descriptions, and instances of opposition or similarity between groups or individual descriptions.

A scale for assessing the complexity of self-conceptions is used to score the interviews. It combines the two methods for building scales described earlier. Scalogram analysis is used to order tasks in terms of complexity, with several ordered tasks differentiating steps within each developmental level as well as between levels. In addition, multiple tasks are used for each step and level to provide independent assessments. This ruler has been used to measure skill complexity varying from single concrete self-characteristics (Level Rp1) through relations of concrete characteristics (Levels Rp2 and Rp3) to abstractions (Level A1) and abstract relations (Levels A2 and A3). The examples in Figure 1 involve mostly abstractions and abstract relations about the Korean girl's important relationships, as well as a few concrete self-descriptions.

In studies using this interview in the United States, Korea, China, and Taiwan, we have tested the properties of a scale for assessing the complexity of these self-constructions based on dynamic skill theory (Fischer, 1980; Fischer, Wang, & Kennedy, in press). Predictions were that the low and high support assessment conditions would show distinct developmental curves, with smooth, continuous growth under low support and nonlinear growth spurts under high support. Figure 2 shows the findings for 72 middle-class students in Seoul, Korea, 6 of each sex in each grade from 8 to 13 (ages 14.5 to 19.5 years, respectively). Note that in the high support condition, the growth curves evidenced spurts at the predicted points, but those for low support produced slower, continuous growth. Similar distinctions between high and low support assessments have occurred across a number of studies using this interview (as well as other kinds of measures) in ages ranging from 7 to 20 years.

The distinctive growth curves across conditions eliminate scale properties as an explanation of the growth spurts because the spurts appear in only one condition. Across studies and ages, the same points on the scale sometimes show spurts and sometimes show continuous growth. The dynamic spurts in performance with high support are properties of supported growth and not results of scale anomalies.

With this straightforward technique for assessing scale properties, as well as similar techniques using different kinds of variations in conditions, researchers can use

LEAST IMPORTANT

LESS IMPORTANT

MOST IMPORTANT

Outgoing Sch +
Relaxed Sch +
Attentive Sch +
Enjoy Sch +
Fun Sib +
Cheerful Rom +
Estranged Sib –
Inferior Sib –
Cheerful Real +
C
Unpretentious Rom +
Peaceful BFr +
Joyful Rom +
Valuable BFr +
Considerate OFr +
1
2
Apologetic Real +
Compassionate Real +
Overjoyful BFr +
Conform OFr +
Honest BFr +
Cheerful BFr +
Fun OFr +
Introvert & Extrovert Real + –
Shy Real +
3
Awkward Rom –
Uncomfortable Fath –
Uneasy Moth –
Dislike Fath –
A
B
Feel good Moth +
Cute Sib +
Comfortable Moth +
4
Peaceful Real +
Bossy Sib –
Troublesome Sib –

Relationships
Bfr: Best Friend   Real: Real Me
Fath: Father   Rom: Romantic Friend
Moth: Mother   Sch: School
Ofr: Other Friend Sib: Sibling

Letters A-C: Opposite
Numbers 1-4: Similar
+: Positive
–: Negative
+ –: Positive & Negative

Fig. 1. Self-in-Relationships Diagram Constructed by a 15-Year-Old Korean Girl in High Support Condition.

multiple-task and scalogram techniques to build effective rulers for assessing dynamic shapes of development. Without research to build such scales, most of human development will remain inaccessible to the tools of nonlinear dynamic analysis.

Using Models as Lenses to Detect Patterns in Data

When developmental data based on strong scales are available, a back-and-forth dialogue between models and data becomes possible. Research on nonlinear developmental dynamics can then move toward a better integration of models and data and produce powerful explanations of a wide range of behaviors. With good data, building and using models becomes straightforward and sometimes even obvious. In addi-
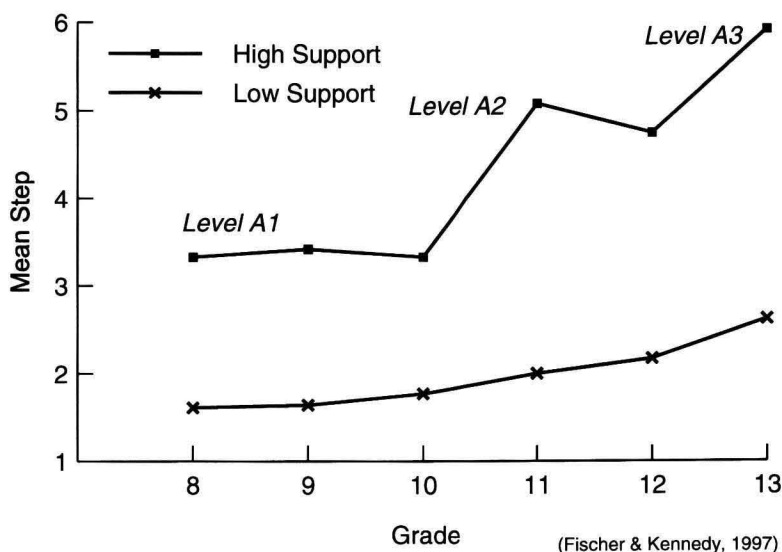
Fig. 2. Hierarchical Development of Self-in-Relationships in Korea

tion to building theory-based models and comparing them with data, investigators can also use data patterns as clues to underlying change processes. They can search for a data pattern that is typical of a certain type of dynamic model and then use that model as a basis for building a hypothesis about the dynamic processes that produce the growth pattern, testing the hypothesis against the data. That is, they can use models as lenses to help detect patterns of change and suggest the kinds of processes producing those patterns.

With the catastrophe-flags approach, researchers examine developmental data to find patterns of change that fit the catastrophe model. Patterns derived from other kinds of dynamic models can be used as well to search for dynamic growth patterns. Examples of models that can serve as lenses include hierarchical and predator-prey growth patterns in both cognitive and brain development.

The growth curve for high support in Figure 2 suggests a hierarchical growth model like the one proposed by Fischer and Kennedy (1997), described earlier — a series of spurts, each followed by leveling off or even a drop. Indeed, that hierarchical growth model was constructed for the Self-in-Relationships interview, based on a skill analysis. The findings in Figure 2 support the model.

Once the model was built, an experimental theoretical question was whether a simple change in a parameter for the same model would produce the growth curve for the low support condition. Or would a different model be required to explain continuous growth under low support? Interestingly, the answer is simple: The same model will produce both stage-like spurts and smooth continuous growth, with the key difference being growth rate. Low growth rates produce smooth continuous growth for many parameter values, while high growth rates produce a series of spurts and drops for the

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same values. This finding from the model may be counterintuitive for many people, because monotonic growth of the kind evident for the low support condition is commonly assumed to stem from linear growth processes, not the complex dynamic processes that we stipulated for hierarchical growth of skills for self-in-relationships.

What other kinds of growth show patterns suggesting dynamic hierarchical growth? Of course there are many cognitive skills that show such growth, which we have reviewed elsewhere (Fischer et al., 1984; Fischer & Rose, 1994). A similar pattern occurs in a surprising domain, however: change in energy in cortical electrical activity as measured by the electroencephalogram (EEG). The scale for EEG energy has good measurement properties and provides an excellent ruler for dynamic assessment of variability and change in cortical activity. The amount of energy in the EEG (measured by the amount of area under the wave form) develops through striking spurts and drops, as shown in Figure 3 for a Swedish study of people varying from 10 to 21 years of age, assessed in a quiet alert state with eyes closed (Matousek & Petersén, 1973). The curve is for one of the standard frequency bands into which the EEG is divided — the alpha band (7.5-12.5 Hz), which is typically strongest in a quiet alert state.

The fit with the standard hierarchical growth pattern is striking, leading Fischer and Rose (1994) to hypothesize that these patterns reflect hierarchical growth of neural networks, with later, more complex networks built on earlier ones. Moreover, the ages for energy spurts correspond approximately to those for spurts in skill development, including that for the Self-in-Relationships interview. We have suggested that neural-network growth and developmental levels are probably two aspects of the same fundamental developmental process.
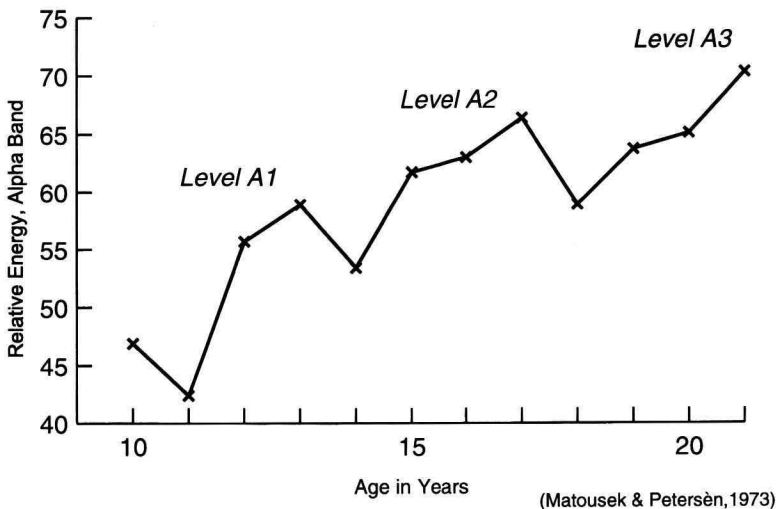

Fig. 3. Hierarchical Development of Relative Cortical Activity (Occipital-Parietal Region) Relative energy is the amount of energy in the alpha band for this region divided by the amount of energy in all frequency bands for this region.

Another characteristic of the EEG, coherence, assesses the strength of connections between cortical regions, and growth patterns of coherence suggest that a second kind of dynamic process in cortical development. Coherence is the cross-correlation between wave forms of the EEG for pairs of cortical regions. High coherence for two regions means that their wave forms are similar, which suggests that the regions are closely connected, even when they are far away from each other in the brain. Because networks involve connections across cortical regions, change in coherence implies change in network characteristics.

Using an extensive data set from a large normative American sample, Robert Thatcher (1994a; 1994b) examined patterns of coherence development. Coherence growth during childhood and adolescence was characterized by oscillations like those in Figure 4. Instead of the hierarchical growth pattern of successive spurts toward higher levels, coherence oscillated up and down, with little or no change in mean level. The oscillations also showed shifts in frequency, which generally occurred at the same ages at which EEG energy showed spurts in the Swedish study. For example, the shift in frequency of oscillation at about 7 years of age in Figure 4 was typical of many coherence growth curves. We hypothesize that these shifts reflect the same reorganizations of neural networks that are reflected in the energy spurts, and we hope eventually to be able to explain the shifts with a dynamic model.
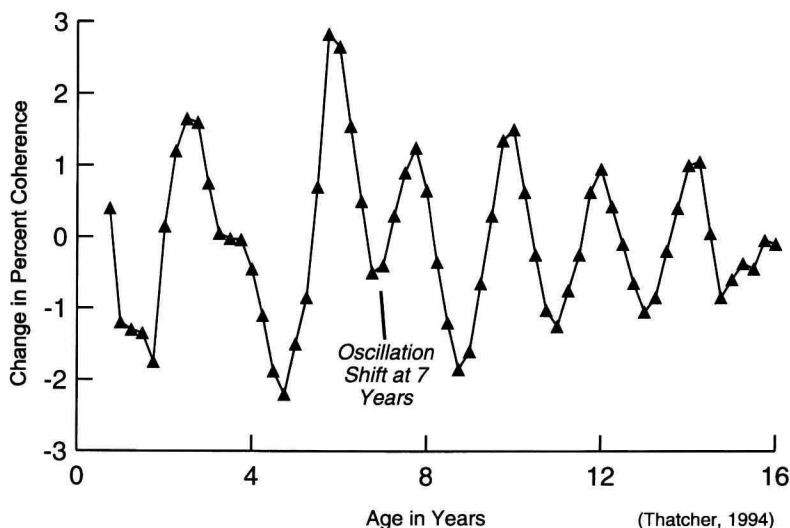

Fig. 4. Predator-Prey Oscillation Pattern in Development of Coherence (Left Frontal & Parietal Regions, F7-P3)

Oscillation like that in Figure 4 is characteristic of another class of nonlinear dynamic models, called predator-prey: One grower uses another to support its growth, in the manner that predators such as foxes use prey such as rabbits for food. A second grower is limited by the first, in the manner that rabbits are eaten by foxes.

Predator-prey processes typically produce oscillation patterns, with populations of both foxes and rabbits oscillating up and down in regular cycles. When researchers see a growth curve showing this kind of oscillation pattern, they can hypothesize a predator-prey relationship in growth processes, build a model, and test the data against it.

Based on this analogy, Thatcher built a predator-prey model of processes connecting left frontal and parietal regions, as well as others. When he tested the model against the data, there was a strong fit, supporting the existence of a predator-prey process regulating the growth of cortical coherence. In Thatcher's findings, the prefrontal cortex was typically the 'predator,' feeding on parts of the cortex further back in the head, such as the parietal 'prey.' Of course, there was no literal feeding, but growth of the prefrontal cortex depended on activity in the parietal cortex; and growth of the parietal cortex was limited by activity in the prefrontal cortex.

Coherence measures similarity in activity patterns between two cortical areas, which is completely different from amount of energy in the EEG in those areas. For example, wave forms can be similar even when they shift to higher or lower general amounts of energy. The co-occurrence of different dynamic models — hierarchical growth for EEG energy and predator-prey growth for EEG coherence — is therefore not surprising. Two different qualities of the same cortical activity exhibit different dynamic growth processes. The energy spurts seem to reflect the way that later networks are built on earlier ones, while the coherence oscillations seem to reflect variations in the meshing of specific pairs of cortical areas in networks. These two patterns suggest rich possibilities for exploring related growth processes that capture several aspects of neural-network growth.

The related models of hierarchical and predator-prey growth in EEG activity may well have a parallel in cognitive development. Just as cognitive level increases according to the hierarchical growth model, connections between cognitive domains may show oscillations fitting a predatory-prey model. This interesting hypothesis remains to be explored.

Conclusion

As this book makes evident, nonlinear dynamic analyses of development are blossoming, and they promise to produce a remarkable profusion of theoretical and empirical flowers, in the best tradition of Dutch botany. For the promise to become reality, however, researchers need to bring together models and data in full interaction instead of following the common pattern of focusing primarily on one or the other. To bring about this joining, it is essential that effective rulers be devised to assess important characteristics of cognitive and socioemotional development, where few worthy developmental scales exist. If there is an Achilles heel to the dynamic approach to development, it is the difficulty of creating effective scales. In domains that lack such scales, meaningful research on the dynamics of growth and development will be virtually impossible.

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