CHILD DEVELOPMENT PERSPECTIVES

The Contribution of Complex Dynamic Systems to Development

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ABSTRACT—***As development is an example of a complex dynamic system (CDS), the theory of CDS can make important contributions to our understanding of the developmental process. However, mainstream research in developmental psychology uses an empirical paradigm that is at odds with what it is purported to explain, namely, that development is a complex dynamic process. Although the number of studies that focus on a process-oriented and dynamic approach of development is growing, this article argues that the field is in need of a theoretical and methodological paradigm shift.***

KEYWORDS—*dynamic systems; complexity; generalization; null hypothesis; developmental processes*

THE CONTRIBUTION OF COMPLEX DYNAMIC SYSTEM TO DEVELOPMENT

The greatest contribution of the complex dynamic systems (CDS) approach to development is that it has given developmental psychology a fruitful theoretical and empirical alternative to the current theoretical poverty of the field and the lack of approaches, theories, and methods that do justice to the nature of development as a complex process. It has done so not so much by introducing a specific new developmental theory, but by providing a new approach, encompassing the way we think theoretically about development, the way we study development empirically, and the statistical and computational methods we apply to verify theories and assign meaning to facts.

This is a major contribution to the field, based on the thesis that development is a prime example of a CDS and that much of the way we currently conceptualize, theorize, and investigate development fails to sufficiently account for its CDS nature.

FEASIBILITY OF THE CDS APPROACH

Among the available examples of work illustrating the feasibility of the CDS approach, the eye catcher is probably Thelen and Smith's (1994) dynamic systems theory of development, exemplified by a theoretical book and a series of great experiments on development as an embodied and embedded process.

Dynamic field theory (Spencer, Perone, & Buss, 2011) is an offspring of the theory of embedded-embodied cognition. It provides a dynamic theory of change grounded in neurologically adequate models. Fogel (2011) represents work on social interaction and development. Studies of social development from my own group[1] include the developmental work on dyadic interaction by Henderien Steenbeek (Steenbeek & Van Geert, 2008a, 2008b), and on identity development and long-term changes in adolescence (Kunnen & Bosma, 2000; Lichtwarck-Aschoff, Kunnen, & van Geert, 2009; Lichtwarck-Aschoff, van Geert, Bosma, & Kunnen, 2008). Marc Lewis (2011), Granic, Patterson, Dishion, and others have made important contributions to the study of interaction and emotion in the context of developmental psychopathology.

As to language development, I refer to my own work on long-term dynamic models of growth and work with Marijn van Dijk and Dominique Bassano (Bassano & van Geert, 2007; van Dijk & van Geert, 2007). Other work on language includes that on word learning by Smith and collaborators (Pereira, Smith, & Yu, 2008), and recent work in the field of first- and second-language acquisition (De Bot, Lowie, & Verspoor, 2007; Larsen-Freeman & Cameron, 2008; van Dijk et al., 2011).

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[1]A complete list of publications by the current author and coworkers can be found at: http://www.paulvangeert.nl/Publication%20List.htm.

Dynamic systems thinking in the field of long-term cognitive development takes various forms. There are not only dynamic field theorists (Schöner, Spencer, in press), but also those working on hierarchical growth models (e.g., Fischer & Bidell, 2006; van Geert & Fischer, 2009). Finally, there is work on brain development from a CDS viewpoint by Lewis (2011) and Kurt Fischer and colleagues (Fischer, 2009).

The developmental systems approach has made important theoretical and related empirical and methodological contributions. Although it does not bear the predicate "dynamic" in its name, it has directly focused on the developmental and system-based nature of the change process (Ford & Lerner, 1992; Molenaar, Huizenga, & Nesselroade, 2003).

Dynamic systems theorists have also made contributions to a variety of methodological issues. One regards discontinuity versus continuity in development (Bassano & van Geert, 2007; van Dijk & van Geert, 2007; Jansen & Van der Maas, 2001; Van der Maas & Molenaar, 1992). Tom Hollenstein's work on the state space grid method (Hollenstein, 2007) has made important advances, as have the development of new statistical modeling techniques for developmental data (Boker & Nesselroade, 2002; Ferrer & Zhang, 2009; Molenaar & Newell, 2010; Molenaar, Sinclair, Rovine, Ram, & Corneal, 2009). Finally, there is the work of Marijn van Dijk, Carolina de Weerth, and myself on intraindividual variability in the context of long-term patterns of developmental change (De Weerth & van Geert, 2002; van Dijk & van Geert, 2007) and work on advanced statistical modeling of intraindividual variability (Deboeck, Montpetit, Bergeman, & Boker, 2009; Von Oertzen & Boker, 2010).

CONTRIBUTIONS TO UNDERSTANDING AND KNOWLEDGE OF DEVELOPMENT

Dynamic systems-based work has made many contributions to our understanding and knowledge of development. First, it has provided models of individual developmental trajectories. The individual, or more generally the individual case (such as real dyads or real groups or real families), is the level of aggregation at which developmental processes take place, and should thus also be the level at which the models are specified. Work on individual trajectory models has shown that such trajectories cannot be reduced to generic trajectory model trajectories based on sample information, plus or minus some random deviations.

The emphasis on the model aspect implies that the CDS-based studies are more than just descriptions of unique and thus nongeneralizable cases. The model is a way of describing an empirical phenomenon on the basis of some underlying theory and thus provides an explicit possibility for generalizing the single-case description to theory that in principle encompasses all individual cases (more on generalization later).

Second, the studies have provided us with new theoretical insights about the nature of the underlying developmental mechanisms by applying dynamic systems modeling based on specific underlying theoretical principles, and by showing that such models provide a good fit to the data. Examples are studies that have shown how performance that researchers formerly treated as basically cognitive, and thus taking place on the basis of internal cognitive manipulation of representations, could be better explained with a dynamics based on perception–action couplings in real time and space. Other examples are the growth models of long-term development in various fields like language development and cognitive skills, which show that a few simple principles of resource-constrained growth, and supportive, competitive, and conditional relationships between variables, can explain a wealth of qualitative and quantitative developmental phenomena.

Third, CDS studies have contributed to developmental research and statistical modeling methods that increase the likelihood of finding or understanding the mechanisms that drive development. They can provide better, theoretically inspired pictures of real-time developmental processes.

Fourth, CDS studies of development have created various fruitful ways of theoretical modeling based on underlying explanatory principles. They have thus provided a complementary approach to the dominant practice of statistical modeling, which primarily focuses on the statistical fit between a particular form of trajectory or distribution and the empirical data, and which in general does not refer to principles that aim to explain where this particular observed form comes from.

Fifth, some of the studies have increased our theoretical understanding of the range of possible developmental patterns that result from recursively or time-serially applying postulated developmental mechanisms such as scaffolding or mutual adaptation between child and caretaker. By doing so, they have illuminated the variety of sources of developmental patterns and have provided better insights into the properties of the developmental mechanisms themselves.

PROPERTIES OF CDS

A CDS is usually defined as any system consisting of many interacting components (for instance, a parent and a child in a spatial environment with various toys and various cognitive, linguistic, motivational, and emotional variables characteristic of a particular child at a particular time). In a CDS, the interaction between the components changes their properties and creates properties on a macroscopic level—a level that exceeds the events on the level of the individual components or that cannot be reduced to the sum of such events (e.g., interaction of the variables of the child system creates a particular long-term pattern of development of those variables). This spontaneous although constrained creation of new properties is known as self-organization, emergence, evolution into attractor states, and so forth. (An attractor state is any state that remains relatively stable for any duration that is meaningful on the level of the time scale under consideration; for instance, on the long-term time scale of development, that duration would be months rather than minutes.) These properties are examples of the nonlinearity of complex systems (for overviews, see, e.g., van Geert, 1994, 2003, 2008; van Geert & Fischer, 2009; van Geert & Steenbeek, 2005).

The general idea is that if a system is complex in the sense that it consists of many interacting components, and if it has sufficient longevity (which is an empirically observable property), it is also very likely that it has properties such as self-organization, emergence, and nonlinearity. This is an important observation, with potentially great consequences for how in principle researchers should study such systems and the kind of theories they need to explain and describe them (I shall come back to this point in my discussion of the null hypothesis).

Complex systems display a mixture of orderliness and randomness. The orderliness on the level of macroscopic properties is often directly related to and maintained by the randomness on the level of the possibly erratic behavior of the components. Complex systems can evolve along different pathways, which emerge because of the particular interactions between the components that constitute the system.

Finally, a dynamic system is a way to explain how the "next" state of the system comes about as a result of its "preceding" state. Thus, the basic form of dynamic systems theory is that of a system of differential or difference equations, and not, as we are used to, a system of equations specifying relations between variables distributed over a population. The difference is not trivial. In fact, it has tremendous methodological and modeling consequences for how we carry out developmental research and theory formation (for discussion, see, e.g., van Geert & Steenbeek, 2005).

IS DEVELOPMENT A CDS?

A developing system is a system of interacting components, including the actions and emotions of a child and of the people with whom the child interacts. Each component is itself a system of interacting components, which is in accordance with another property of CDS, namely, that such a system forms a hierarchical structure. For instance, the brain is organized into various regions with specific functions, working together with other regions. Physically, a person is a system of functional components such as the brain, the senses, motor organs, and so on. A person is a member of a family, which is a network of interacting agents with particular interests and capabilities that change as a consequence of their interactions.

In the aforesaid examples, properties of the components of the system change as they interact with one another. For instance, as the developing person learns and develops, parents or teachers change the tasks they assign, the expectations they have, the opportunities they provide, and so forth.

The interactions among the components lead to emergent phenomena, including the creation of novelty. A prime example is the brain, where the connections of specialized regions lead to macroscopic behavior that exceeds the properties of each of the separate regions. Cognitive development is most likely also an example of new properties emerging out of the dynamics of the developmental process. It is remarkable that many eminent developmentalists are or have been so hesitant to accept the hypothesis of cognitive development as emergence of new properties, and are instead implicitly sticking to the hypothesis of preformation followed by basically linear accretion of elements.

One important aspect of a CDS is that it entails a theory for explaining how one state of the system changes into another over the course of time. The operation that provokes this change is called the system's evolution term or evolution rule. Formally, the evolution term is a mathematical operation on the current state space properties of the system. However, this operation must express some real mechanism of change. For instance, a dynamic system in which change is governed by an evolution term expressed as a simple addition is formally equivalent to a system in which learning or development takes place by simple accretion or accumulation of learning experiences, the content of which in no way depends on the current properties of the system, such as on how developmentally advanced it currently is. It is unlikely that such a simple, state-independent mechanism actually governs development. However, the popular simple linear regression model with time as an independent variable is formally equivalent to a differential equation model with a linear additive term. Such linear regression models are thus very unlikely models of change. These models abound in developmental psychology because they are mostly applied to aggregations of individual process data and are used as *statistical* models of such data. However, models based on aggregated data from individuals have no logical bearing on models of individual processes. Molenaar (2008) calls this the ergodicity principle. He and his collaborators have shown that the implicit step, so common in the behavioral sciences, from sample-based research to individual process statements is often demonstrably incorrect.

In developmental psychology, there is relatively little theoretical work on the properties of the postulated developmental mechanisms, such as work that studies what type of developmental patterns such mechanisms can eventually produce, and also whether these mechanisms are—at least theoretically—capable of generating the developmental patterns they are assumed to explain. This question of turning models of mechanisms into dynamic systems models has intrigued me for a long time, and together with my collaborators I have tried to model several types of such phenomena (see, e.g., Kunnen & Bosma, 2000; Steenbeek & van Geert, 2008a, 2008b; van Geert, 1991, 1994, 1998; van Geert & Steenbeek, 2005). These models have led to interesting discoveries of potential developmental patterns and of the nonlinearities that such models are capable of producing. We have also been able to empirically verify such models, such as the concern-based agent model I have worked on with Henderien

Steenbeek (Steenbeek & van Geert, 2008a, 2008b) and a longitudinal model of parental adaptation to the child's learning of language (van Dijk et al., 2011).

The main question is of course whether the classical developmental mechanisms are indeed "serious" candidates for developmental mechanisms, or whether they are just the remnants of the distant past. I think they are serious candidates (see van Geert, 1998), but they are clearly higher order or macroscopically defined mechanisms. Compare the Vygotskyan mechanism of the zone of proximal development (ZPD) and of interiorization with the mechanism implied in dynamic field theory (DFT). DFT is rooted in neurologically plausible models and has helped generate specific and empirically verified predictions. ZPD theory functions on a considerably higher descriptive level. It invokes no direct reference to the brain, but focuses on certain qualitatively defined macroscopic processes (see, e.g., van Geert & Steenbeek, 2006).

To conclude, CDS theorists have given sufficient arguments for and examples of development as a CDS to spark interest among developmental psychologists for a theory of processes that has shown its worth in a wide variety of scientific disciplines.

DEVELOPMENTAL PSYCHOLOGY IN LIGHT OF CDS

The dominant empirical paradigm of developmental psychology, and in most other areas of psychology for that matter, is something we can loosely call sample-based explanation of variance. This empirical paradigm, I believe, is strangely at odds with the nature of what it is purported to explain, which is human development. It works perfectly well with sample-based questions, because it is a sample-based methodology. Examples of such questions are: "What is the most effective intervention or treatment for some problematic property such as aggression or bullying in the classroom, given that effectiveness is a sample-based criterion?" This is the kind of question a policy maker will ask. However, questions such as "How does bullying come about in a classroom, how does it evolve, by what mechanisms, and how does it affect participants?" are about how and why actual change occurs. These questions can be fruitfully studied only by actually following and observing such processes where and when they occur. I referred before to the ergodicity or homology principle, which says that a model based on samples of individuals does not automatically generalize to a model of individual processes. Hence, we should not try to infer knowledge of such processes from data that cannot tell us how such processes actually work.

Although there are many arguments that CDS theory is the "natural" theory for developmental psychology, it is also obvious that CDS has hardly caught on in the field. Most of the reasons are related to the paradigmatic methodological and theoretical choices the field made a long time ago.

A first factor, which has a strongly conservative effect on the way we do research and try to build theories (or avoid doing so) and which hinders the spread of dynamic systems approaches in developmental science, is the currently dominant definition of *generalization*. Epistemologically, an observation is assumed to have little scientific sense if it remains confined to its specific and unique circumstance of observation. Its sense derives from its effect on more general and encompassing statements or observations. In the behavioral sciences, generalization is almost exclusively tied to sample generalization—the question of whether a current observation of a distribution of properties in a sample carries information about the distribution of those properties in another, perhaps bigger sample. Because of this highly impoverished notion of generalization, case-based studies, studies with small sample sizes, individual process studies, and so forth are in general eschewed and too often dismissed as scientifically irrelevant. This narrow approach to generalization is related to a rather superficial definition of "theory" in much of developmental research. A theory of development should in fact be a theory of long-term change, and such theories should explain how basic developmental mechanisms can generate specific developmental patterns. In principle, as a theory, CDS can provide predictions and models of developmental trajectories that single case studies can fruitfully examine, provided that the cases are well chosen. The generalizability of these studies relates to how they link to an underlying theory (Molenaar & Campbell, 2009; Yin, 2009). There is an interesting contrast between studies in language development, which mostly are based on individual or have small sample sizes, and studies in most other fields of development. For students of language development, single case studies have a direct bearing on the underlying theory, and only an indirect one on the population of language learners. In summary, a truly general theory of developmental processes is one that can be "individualized"—it can generate theory-based descriptions of individual trajectories in a nontrivial sense.

A second series of factors that hinders the CDS approach results from the difficulties of *time-serial data collection* inherent to its subject. Interesting and sufficiently dense process data of development are difficult to obtain, and the detailed study of a single developmental trajectory requires an awful lot of effort and time. However, technological developments ranging from portable recording devices to sophisticated software for observational data analysis make it increasingly easier for the researcher to collect dense and relevant time-series data. A related issue is the current lack of user-friendly statistical software for fitting dynamic models to time-serial data. As soon as user-friendly packages become available, the CDS approach may rapidly grow.

Another related issue that hampers the progress of CDS is the view on *measurement error*. Dense individual time series tend to show considerable fluctuation, which is often seen as an expression of uninformative measurement error. The alleged error is often reduced by sampling across individuals or relatively long periods of time, which, as several studies have shown, results in a significant loss of developmentally relevant information (see, e.g., Bassano & van Geert, 2007; van Geert & van Dijk, 2002). Yet another issue is that of the complexity of developmental data, which are often of a multivariate nature. It is possible to reduce the complexity of fluctuating multivariate data sets by describing them in the form of *latent variables.* To obtain these latent variables, researchers often resort to sampling across individuals, thus losing the information about the underlying individual-based dynamics. However, recent methodological developments allow us to estimate latent variables in individual time-series data. On the other hand, if developmental researchers focus on well-considered variables, they should not too easily discard the wealth of their observations by prematurely using statistical reduction techniques; instead, they should invest time in a critical and thorough exploration of their data, aided by adequate visualization and data-mining techniques.

A third factor that hampers the spread of CDS is related to the issue of the *null hypothesis*, which is a basic ingredient of statistical tests, or to the issue of prior beliefs as in Bayesian statistics. In both cases, this issue deals with what you believe to be the case until new information comes in and eventually changes that theory or belief.

In the behavioral sciences, we are used to null hypotheses that refer to the "simplest possible theory," which is usually based on the assumption of linear and random systems. If you know nothing about the world, the simplest possible theory is the best bet. However, we already know an awful lot about the world, and we should therefore use the simplest possible *plausible* theory. If a developing system is complex, it follows that development is likely to show self-organization, emergence, attractor states, critical states, discontinuities, and so forth. Take, for example, the discussion on discontinuity in developmental change. The standard null hypothesis predicts linear continuity until the opposite has been convincingly shown. However, if linear change is an exception instead of a rule in complex systems, the null hypothesis should be the reverse: Accept discontinuity unless the opposite—that the change is continuous—is convincingly shown. A comparable issue concerns the significance of fluctuation or intraindividual variation in the context of macroscopic orderliness. The classical solution is to describe an observation as a superposition of some stable term and some independent random effect (as in the true score plus measurement error model). However, orderliness and randomness are deeply related to one another in CDS and should therefore be studied together.

A fourth series of factors is of a pragmatic rather than a paradigmatic nature, although they are related to the paradigmatic problems I discussed before. For young scientists wishing to make a career based on publications generated in a relatively short period (say, the pretenure track period), explorations off the beaten track are often unattractive. In addition, there is relatively little opportunity for training in dynamic systems theorizing and methodology, and because of the lack of knowledge, dynamic systems methods, simulations, and theories may appear too daunting for those who are new in the field. In addition to that, dynamic systems theory as applied to developmental psychology is far from a single and coherent unity. Despite general agreements about dynamic systems principles, CDS theorists sometimes disagree on what counts as an adequate CDS model of development (Lewis, 2000; van Geert & Fischer, 2009). Thus, researchers wishing to apply CDS in their prospective studies may be hindered by the variety of possible choices.

THE NEXT 20 YEARS

The challenges and necessary directions for the next 20 years are simple and follow from the discussion in the preceding section. The major challenge is to establish a paradigm shift in developmental thinking. The pessimistic stance is that such a paradigm shift will not occur, primarily because the forces that act against paradigm shifts in developmental psychology—if not in all scientific disciplines—are now too strong to allow for paradigm shifts. The less pessimistic prediction is that CDS will not diffuse into developmental psychology as a whole, as I would hope, but will survive as yet another subdivision in developmental psychology (some developmentalists work on bullying, others on theory of mind, still others on dynamic systems, and so on). The pragmatic interests of continuation may be too great; the sociology of science and the related issues of career concerns, and the sheer mass of the discipline in terms of professionals and researchers, may make such a paradigm shift unlikely. The optimistic prediction is that, in line with CDS theory itself, the growing numbers of currently rather isolated islands of CDS applications in the world will finally form a critical mass, leading to a tipping point phenomenon from which what Isabel Granic (2010) recently called a velvet evolution of developmental psychology may emerge.

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