Cognitive Development 27 (2012) 401–418

Contents lists available at SciVerse ScienceDirect

Cognitive Development

Contributions of dynamic systems theory to cognitive development

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ARTICLE INFO

Keywords:
Dynamic systems theory
Spatial memory
Perseveration
Neural networks
Object concept

ABSTRACT

We examine the contributions of dynamic systems theory to the field of cognitive development, focusing on modeling using dynamic neural fields. After introducing central concepts of dynamic field theory (DFT), we probe empirical predictions and findings around two examples—the DFT of infant perseverative reaching that explains Piaget's A-not-B error and the DFT of spatial memory that explain changes in spatial cognition in early development. Review of the literature around these examples reveals that computational modeling is having an impact on empirical research in cognitive development; however, this impact does not extend to neural and clinical research. Moreover, there is a tendency for researchers to interpret models narrowly, anchoring them to specific tasks. We conclude on an optimistic note, encouraging both theoreticians and experimentalists to work toward a more theory-driven future.

Mathematical modeling of human behavior has a long history dating back to the early 19th century (Fechner, 1860; Weber, 1842–1853). The history of formal modeling in developmental science is much shorter. Thus, this special issue offers a welcome opportunity to evaluate the contributions of computational modeling to developmental science in its infancy, when prospects for the future are just beginning to come into focus.

Our article emphasizes a particular type of computational modeling using dynamic neural fields (DNFs) that has emerged from the broader framework of dynamic systems theory (DST). Our goal

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0885-2014/$ – see front matter
http://dx.doi.org/10.1016/j.cogdev.2012.07.006

is to highlight how dynamic field theory (DFT) has been useful in understanding cognitive development and generating new empirical predictions and findings. We focus on two examples—the DFT of infant perseverative reaching (Thelen, Schöner, Scheier, & Smith, 2001) proposed to explain the classic Piagetian A-not-B error, and the DFT of spatial memory used to explain changes in spatial cognition in early development (Spencer, Simmering, Schutte, & Schöner, 2007). These examples are ideal in the context of this special issue because in each case there are alternative formal theories. This allows us to discuss the impact of DFT in particular as well as the impact of formal modeling more generally. Analyses of the literature in each domain reveal that computational modeling is making inroads into mainstream cognitive development; however, there is much to be done to fully integrate formal approaches into mainstream cognitive development. Doing so will require effort from both theoreticians and experimentalists.

1. Dynamic systems theory overview

DST emerged within developmental science within the last 20 years. It is based on advances in physics, mathematics, biology, and chemistry that have changed our understanding of non-linear, complex systems (Prigogine & Stengers, 1984). The developmental concepts that underlie DST are based on pioneering work by Thelen and Smith (1994) as well as early work from other theoreticians such as Fischer (Fischer & Rose, 1996), Van Geert (1997, 1998), and Molenaar (Molenaar & Newell, 2010; Van der Maas & Molenaar, 1992).

DST has made major contributions to developmental science by formalizing multiple concepts central to a developmental systems perspective (Lerner, 2006). The first is that systems are self-organizing. Complex systems such as a developing child consist of many interacting elements that span multiple levels from the genetic to the neural, the behavioral, and the social. Interactions among elements within and across levels are nonlinear and time-dependent. Critically, such interactions have an intrinsic tendency to create pattern (Prigogine & Nicolis, 1971). Thus, there is no need to build pattern into the system ahead of time—developing systems are inherently creative, organizing themselves around special habitual states called “attractors.”

The notion that human behavior is organized around habits dates back at least to James (1897). But DST helps formalize the more specific notion of an attractor, providing tools to characterize these special states (Van der Maas, 1993; Van der Maas & Molenaar, 1992). For instance, a typical way to characterize a habit is to simply measure how often the habitual state is visited. Importantly, DST has encouraged researchers to also measure how variable performance is around that state and whether the system stays in that state when actively perturbed. This is particularly revealing over learning and development because habits often become more stable—more resistant to perturbations—over time.

Within this context, DST also helps clarify the relation between two related concepts central to developmental science—qualitative and quantitative change (Spencer & Perone, 2008; Van Geert, 1998). Qualitative change occurs when there is a change in the number or type of attractors, for instance, going from one attractor state in a system to two. Such special changes—called bifurcations—can arise from gradual, quantitative changes in one aspect of the system. A simple example is the shift from walking to running. As speed quantitatively increases across this transition in behavior, a sudden and major reorganization of gait occurs having a qualitatively new arrangement of elements (Diedrich & Warren, 1995).

Gait changes are one of the classic examples first studied by researchers interested in applying the concepts of DST to human behavior. This early work led naturally to the use of dynamic systems concepts to explain transitions in motor skill both in real time and over learning and development (Adolph & Avolio, 2000; Fogel & Thelen, 1987; Thelen, 1995; Thelen, Corbetta, & Spencer, 1996; Whitall & Getschell, 1995). One conclusion from these studies is that the brain is not the “controller” of behavior. Rather, it is necessary to understand how the brain capitalizes on the dynamics of the body and how the body informs the brain in the construction of behavior (Thelen & Smith, 1994). This has led to an emphasis on embodied cognitive dynamics (Schöner, 2009; Spencer, Perone, & Johnson, 2009), that is, to a view of cognition in which brain and body are in continual dialogue. We return to this theme in our discussion of dynamic field theory.