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Review

Change occurs when body meets environment: A review of the embodied nature of development[1]

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Abstract: The purpose of this paper is to outline the challenges of psychological research in addressing the mechanisms of emergence: how new behavioral patterns and cognitive abilities arise from the interaction of an organism with its environment in real time. We review some of the empirical studies on infant development with reference to Dynamical Systems accounts and relevant views such as the ecological approach to perception and action, and cover topics ranging from early motor skills to goal-directed locomotion and to higher cognitive development. The central claim is that the results of these studies are essentially related: they suggest that there is a fundamental connection among perception, motor behavior, and cognition. In addition, we recount our attempt to re-enact the situatedness and temporal structure of the decision-making processes of human infants by using an autonomous robotic device. We conclude by highlighting several insights from the broad spectrum of studies looking into the embodied nature of adaptive behavior. In our view, such studies are making a profound contribution to uncovering the emergent mechanisms of intellectual and bodily activity throughout development.

Key words: development, embodiment, Dynamical Systems approach, perception and action, ecological approach.

How does an appropriate behavioral pattern emerge moment by moment while an infant or child experiences its changing environment? How do we learn skills for goal-directed activities that meet task demands? These remain among the enduring questions of development. The primary purpose of this paper is to review the challenges facing developmental psychology and related fields in trying to understand the mechanisms that underlie the emergence of new behaviors and competences: how patterns arise from the interaction of an organism with its environment in real time.

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We focus on two current directions of theoretical thinking, the Dynamical Systems approach (Thelen & Smith, 1994) and the ecological approach to perception and action (Gibson, 1979, 1988). These two perspectives are based on the "beliefs in the primacy of perception and action as the basis for cognition, and in the fundamental role of exploration" (Thelen & Smith, 1994, p. xxi). We will cover topics ranging from early motor skills (e.g., alternating stepping) and goal-directed locomotion to higher cognitive development (e.g., perseverative reaching in a task analogous to Piaget's A-not-B error (Piaget, 1954)). We will also present neurally inspired mathematical models (Thelen, Schöner, Scheier, & Smith, 2001) that formalize this theoretical thinking and will demonstrate the capacity of these models to provide process accounts of behavior by implementing the models on autonomous robots. The studies that we will review provide evidence against the view that developmental change is dominated by a single cause (e.g., a "genetic program"). Rather, they show that development is a product of complex interactions among multiple factors, such as task-specific demands, perception of affordances of the environment or of objects in the environment, and the behavioral history on multiple time scales from a moment in time to the months and years of development.

We will conclude with insights from a broad spectrum of research that examines how adaptive behavior and cognition is assembled and begins to uncover the emergent mechanisms of embodied cognition. These insights are consistent with other perspectives of cognitive development which postulate that cognition (or knowledge) is inseparable from the cognitive processes that govern perceiving and acting, and is in sharp contrast to older views that categorically separated cognitive processes from sensory-motor processes (Smith & Sheya, 2010). One goal we set ourselves for this paper is to expose readers to this paradigm shift in developmental studies, which leads to a new emphasis on the seamless integration of perception, action, and cognition in real time. We believe that this change in emphasis has ample implications for developmental studies and various other research fields related to the science of intelligence.

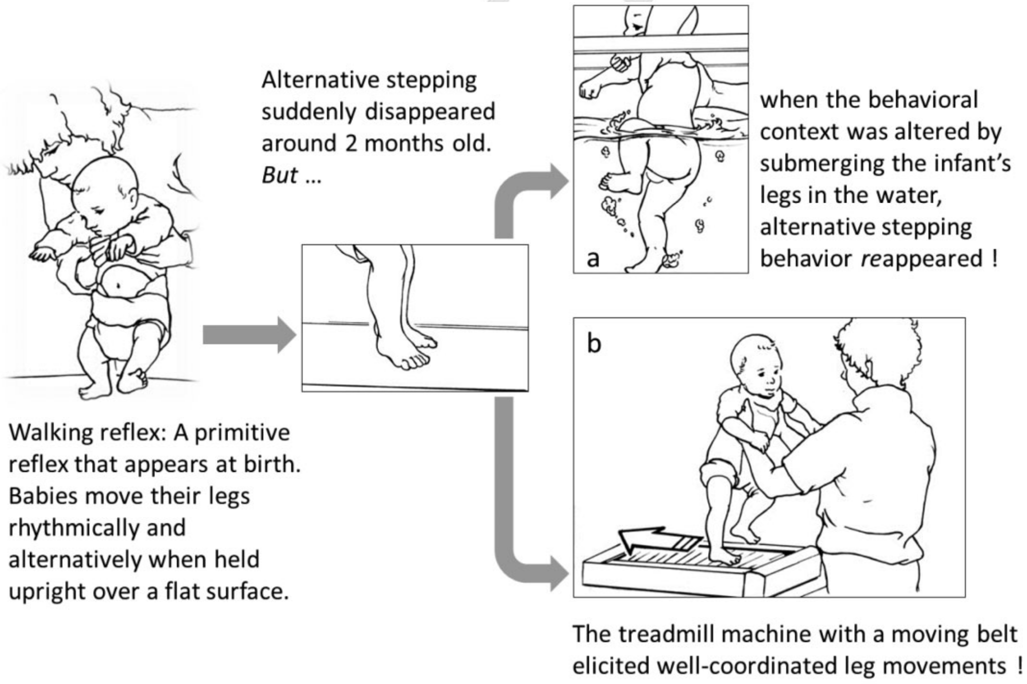
Changes in perception and action through the body-environment link

"Very simple changes in the infants or their environmental contexts shifted the developmental path of a transition believed to be the inevitable consequence of brain maturation" (Thelen & Smith, 1994, p. 12). This quote is from the book, *A Dynamic Systems Approach to the Development of Cognition and Action*, in which Esther Thelen and Linda Smith brought to bear principles of nonlinear dynamics on questions in the field of developmental psychology. Their work was a major breakthrough toward understanding how behavior changes over time. They challenged classical theories of development that had considered development as a product of brain maturation. We devote this section to illustrating the essence of Thelen and her colleagues' work on motor development, showing that "*behavioral expression* is entirely context-dependent" (Thelen & Smith, 1994).

Body meets environment

The first example is the "mystery" of baby's stepping movements that appear at birth. It is generally observed that babies may spontaneously move their legs rhythmically in an alternating pattern when held upright to just touch a flat surface. This stepping reflex, one of a variety of newborn primitive reflexes, looks very much like well-coordinated "stepping" behavior. At approximately 2 months of age, however, this movement suddenly disappears (Figure 1), and then reappears at approximately 1 year of age when babies are about to walk independently. Here is the mystery: why does the newborn baby's stepping behavior disappear even though it needs to reappear later as a necessary component of walking? The prevailing explanation of this developmental phenomenon is that this leg movement is generated by subcortical output (a genuine reflex), which is inhibited as the cerebral cortex matures and differentiates, until it disappears. Then, through a period of brain reorganization, the stepping movement reappears in a new form as a component of voluntary walking (Cole, Cole, & Lightfoot, 2005; Zelazo, 1983).

In contrast to the accepted view, Thelen and her colleagues described a very different picture. In longitudinal studies of the anatomical and behavioral development in infants, they focused on the relationship between individual differences in the rate of weight gain and the period in which the stepping behavior disappears. They found that babies who gained weight faster stopped stepping earlier. This observation led the researchers to an alternative explanation: the disappearance of the stepping behavior might be caused by a discrepancy between the rate of the baby's physical growth and their muscle strength. That is, the rate of weight gain in the legs gets ahead of the rate of increasing muscle strength, resulting in a relative lack of muscle power to lift up the heavier legs against the force of gravity. The researchers devised a clever experiment to test the idea (Thelen, Fisher, & Ridley-Johnson, 1984): they submerged older infants, whose stepping movements were beginning to decrease, in waist-level water and witnessed that the frequency of the infants' stepping increased straightaway (Figure 1, panel a). This occurred because the buoyancy of the water reduced gravity's pull and cancelled the disequilibrium between the weight on the infants' legs and their muscle force. The researchers further demonstrated that the appearance of the stepping behavior could be controlled by contextual manipulations. Infants of approximately 7–10 months old, whose stepping behavior had not yet reappeared, were held over a treadmill so that they were upright and their feet touched (Thelen, 1986). When the machine was turned on and the belt started moving, the infants showed well-



Alternative stepping suddenly disappeared around 2 months old. *But* ...

Walking reflex: A primitive reflex that appears at birth. Babies move their legs rhythmically and alternatively when held upright over a flat surface.

when the behavioral context was altered by submerging the infant's legs in the water, alternative stepping behavior *re*appeared !

The treadmill machine with a moving belt elicited well-coordinated leg movements !

Figure 1 Disappearance of a newborn baby's stepping behavior and its reappearance in altered behavioral contexts. Reproduced from *A Dynamic Systems Approach to the Development of Cognition and Action*, by E. Thelen and L. B. Smith, 1994, p. ••. Copyright 1994 by the MIT Press..

coordinated leg movements. The infants adjusted the rate of their stepping when the speed of the moving belt was varied (Figure 1, b).

These data show that the emergence of movement patterns in infants is subject to contextual influences.[3] In terms of the behavioral manifestation of competences, the developmental path is not linear. Brain maturation alone is not the single cause driving developmental change. Thelen and Smith describe this viewpoint succinctly in this quote: ". . . walking development is sensitive to organic and environmental events to a degree not previously suspected. Whatever the course of brain development, behavioral expression is entirely context-dependent" (Thelen & Smith, 1994, p. 16). Development is a product not of a program, but of complex interactions among multiple factors including the agent's body (sensory-motor foundation), and environmental and task constraints. In nonlinear dynamics, solutions may abruptly emerge or disappear as parameters or boundary conditions vary in a graded way. Such phenomena are called instabilities or bifurcations in the mathematical theory of Dynamical Systems and they had previously been used to account for experimental observations of instabilities in movement coordination (Schöner & Kelso, 1988). Thelen and Smith applied the analogy between instabilities and emergence to developmental psychology, and this ultimately led to a new theoretical framework known as the Dynamical Systems approach to development.

Dynamic explanation of a goal-directed action

The idea that behavioral change emerges from the body-environment link and complex interactions among multiple factors also applies to situations where infants execute voluntary and goal-directed actions. For instance, when we show infants an attractive toy, they will reach for it and attempt to grasp it. It is known that reaching and grasping behavior in healthy infants appears at approximately 4 months of age, and this seemingly reliable milestone of behavioral development is frequently used as a diagnostic sign of normal development (Rochat, 2001). In actual fact, the developmental path toward reaching behavior in infants is quite variable, which contrasts with the "universal" picture often assumed to be the case (Thelen et al., 1993; Thelen, Corbetta, & Spencer, 1996). Thelen and colleagues conducted weekly observations of infants' reaching during the first year of life and found that there were clear individual differences in motor styles: at onset, the pattern of some infants' movements was characterized as fast and vigorous (e.g., flapping and throwing around the arms energetically), whereas other infants made slower and more tempered movements. Moreover, the infants gradually changed and tuned their motor profiles in different ways: the more active reacher learned to dampen the overflowing vigor to stabilize the trajectory of his arms, whereas the less active reacher learned to raise her arms more energetically against the force of gravity. That is, unlike the accepted explanation, voluntary reaching in infants emerges from individual solutions founded on the intrinsic dynamics specific to each infant's body and limbs. In this sense, reaching behavior is organized by integrating the infant's intention (i.e., motivation to grasp the toy) with the unique constraints of an individual's body dynamics. Although healthy infants eventually learn to reach in similar fashion, the learning processes underlying their success are not universal but instead various and individual (Spencer et al., 2006). This result supports the idea that the intrinsic dynamics of an agent's body plays a crucial role in the achievement of goal-directed actions.

Young children's ability to perceive possibilities for action (i.e., affordance) is another instance of context-dependent behavior. In a study by Berger and Adolph (2003), healthy

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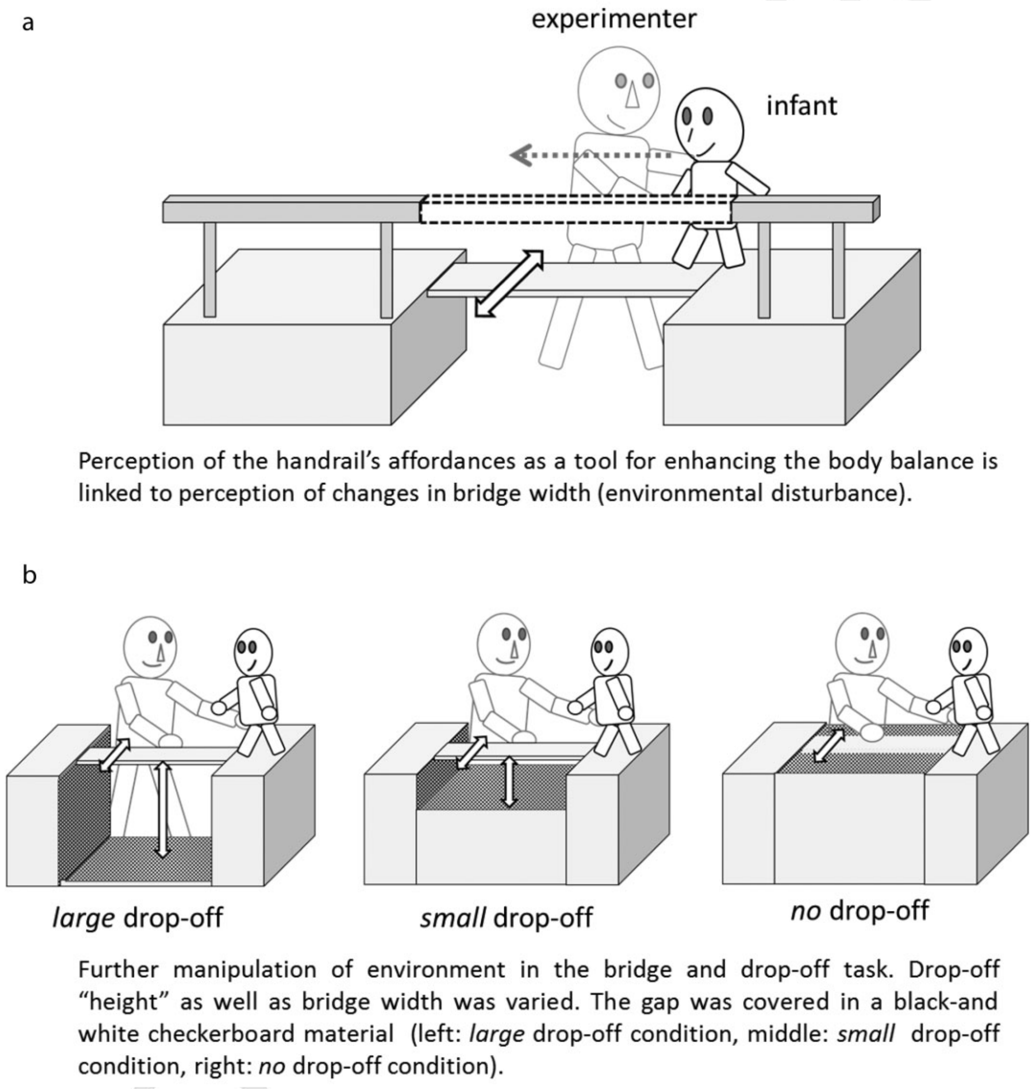
[3] Thelen and Smith (1994) argued as follows: "treadmill stepping was not reflexive, in the sense that a reflex is a stereotyped response to phasic stimuli, and where the magnitude of the response is independent of the strength of the stimuli. Rather, treadmill stepping was flexible and adaptive in a functionally specific way" (p. 13).

16-month-old toddlers who could already walk were encouraged by their parents to cross over a bridge between two platforms with or without a handrail (Figure 2, panel a). The bridge was varied in width from 12 cm to 72 cm, and a handrail was provided in some trials, but not in others. The toddlers ran over on the widest bridge (72 cm) without hesitation. In fact, they spent a minimal amount of time exploring the platform and nearly ignored the presence of the handrail. However, on narrow bridges (12–24 cm), the toddlers attempted to walk only



Perception of the handrail's affordances as a tool for enhancing the body balance is linked to perception of changes in bridge width (environmental disturbance).

Further manipulation of environment in the bridge and drop-off task. Drop-off "height" as well as bridge width was varied. The gap was covered in a black-and white checkerboard material (left: *large* drop-off condition, middle: *small* drop-off condition, right: *no* drop-off condition).

Figure 2 The impact of environmental disturbances on the behavioral decision-making and perception of affordances for action. (a) Reproduced from "Infants use Handrails as Tools in a Locomotor Task," by S. E. Berger and K. E. Adolph, 2003, *Developmental Psychology*, *39*, p. ••. Copyright 2003 by the American Psychological Association. (b) Reproduced from "No Bridge too High: Infants Decide Whether to Cross Based on the Probability of Falling not the Severity of the Potential Fall," by K. S. Kretch and K. E. Adolph, 2013, *Developmental Science*, *16*, p. ••. Copyright 2013 Blackwell Publishing Ltd.

when the handrail was available. They avoided crossing when the handrail was absent. The time spent in exploratory behavior was longer when toddlers were confronted with narrow bridges.

A recent follow-up of this study pinpointed the perceptual basis for the toddlers' decision. In Kretch and Adolph (2013) the height of the drop-offs under the bridge was varied from large (71 cm in height), to small (17 cm in height), to no drop-off (Figure 2, panel b). The width of the bridges (2–60 cm) continued to be varied as well. For 14-month-old toddlers, the width alone, not the drop-off, predicted if they would cross! In fact, when the bridge was too narrow for locomotion, infants occasionally refused to cross over the bridge and instead descended into the drop-off by stepping, crawling and so on.

The behavioral decision of the toddlers as to whether to cross the bridge or stay on the platform emerged from their active exploration of the possibility of realizing a safe crossing. That exploration and decision is related to immediate perceptual factors, that is, the width of the bridge and the presence of a hand-rail, not to more abstract knowledge, such as how a high drop-off is dangerous. The toddlers accurately evaluated their own motor ability to achieve the goal (crossing the bridge safely) by monitoring changes in the task setting that occurred in real time (wide/narrow bridge width and with/without handrail). The children made real-time, online, dynamic decisions that came not from stored knowledge but from learned online perception.

Beyond the legacy: Linking perception/action cycles to cognitive development

The relationship between the Dynamical Systems approach and the ecological approach to development can be clarified around this example. In the Dynamical Systems approach, the different factors that impact on behavior are conceived of as "forces" in neural dynamics, ranging from intrinsic factors that reflect the neural circuitry to environmental factors that act through sensory input. The joint effect of these forces is the emergence of a stable state that becomes visible as overt behavior. As conditions vary, any individual factor may play a pivotal role that brings about stability and thus emergence of the competency. Changing the environment (e.g., submerging in water, providing a handrail or not, or changing the width of the bridge) led children to (re-)organize their behavioral patterns. Moreover, the intrinsic dynamics of each individual determine possible and effective actions to achieve a goal. These examples illustrate that immediate sensory-motor experiences and a child's active engagement in a task are critical to a child.

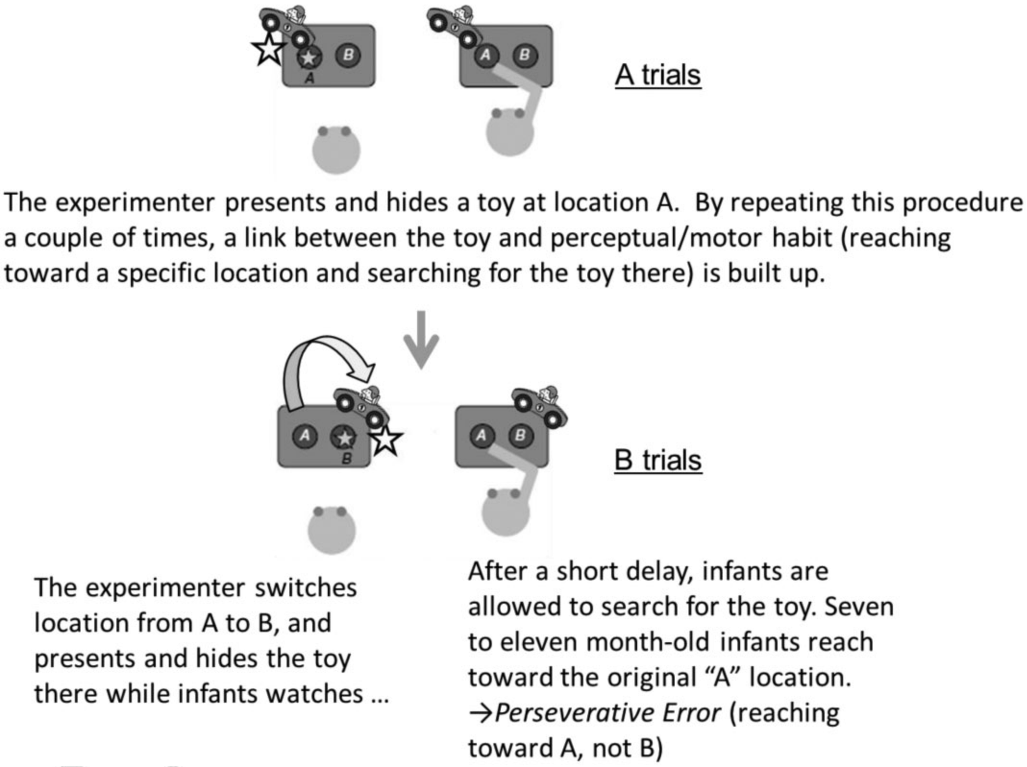
Gibson's (1979) notion of affordance coheres with this idea. Information pick-up and direct perception of affordances are possible because the sensory-motor system has a neural dynamic whose intrinsic structure enables a particular action when the appropriate sensory input is available. Moreover, the sensory array is but one factor in selecting action. A graded difference in sensory information may lead to the emergence of the complete behavior. There is no need, in this view, to specify behavior in explicit detail or to compute from scratch the parameters of action. Instead, the relationship between perceiving and moving is reciprocal and cyclic (Gibson, 1979, 1988): "So we must perceive in order to move, but we must also move in order to perceive" (Gibson, 1979, p. 223). Through moving in the environment, we continuously receive information from proprioceptive and haptic senses, and this information is tightly coupled with information received from external senses such as visual and auditory perception. Motor behavior itself, thus, should be considered "an integral part of the ensemble of all our experience" (Thelen, 2000a, p. 394).

Gibson (1988, 1991) argued that cognitive development builds on information seeking and gathering (e.g., discovering affordances in the world) through exploratory activity: "Cognition begins as spontaneous exploratory activity in infancy" (Gibson, 1991, p. 602). We will see below how the Dynamical Systems approach may turn this hypothesis into an operational account of learning in which memory traces of motor activity shift the point at which a learned behavior emerges.

How is perceiving and moving in an environment related to higher cognition, which lacks the immediacy of the sensorimotor domain? Theories of cognitive development have long assumed that as our mental activity becomes increasingly abstract over development, so that perception and movement are gradually set aside and become mere “bystanders” (Smith & Sheya, 2010; Thelen, 2000b). In what follows, we shall review both empirical and simulation studies initiated by Thelen, Smith, and colleagues that illustrate cognition is inseparable from perception, and bodily experience in the A-not-B error first studied by the philosopher and developmental thinker Jean Piaget (1896–1980) provides the paradigm. We will first review its canonical interpretation and then contrast it with the Dynamical Systems approach, including our own work.

Piaget’s A-not-B error and challenges to the prevailing interpretation

When children aged 7–11 months search for a hidden toy, they may perseverate error, making the A-not-B error (Piaget, 1954; Figure 3). In the task, the experimenter presents a toy to an observing infant, and while they watch, hides the toy at a location “A,” a trough in a box that is then covered up. After a short delay, the infant is allowed to reach toward that location (e.g., by moving the box into the reaching space of the infant) and to discover the toy there. After repeating this procedure a couple of times, the experimenter switches from location “A” to a new location “B” and hides the toy there while the infant watches. Then, when the infant is allowed to search for the toy, they



The experimenter presents and hides a toy at location A. By repeating this procedure a couple of times, a link between the toy and perceptual/motor habit (reaching toward a specific location and searching for the toy there) is built up.

The experimenter switches location from A to B, and presents and hides the toy there while infants watches ...

After a short delay, infants are allowed to search for the toy. Seven to eleven month-old infants reach toward the original “A” location. →*Perseverative Error* (reaching toward A, not B)

Figure 3 Schematic description of the canonical A-not-B error task.

perseveratively reach toward the original location "A." This perseverative tendency to reach toward the location first experienced is called the A-not-B error. It occurs even though the infant watches the whole sequence of events in the task.

According to Piaget's original interpretation (Piaget, 1954), the A-not-B error is due to an infant's incomplete object concept and associated lack of object permanence: Infants fail to understand that an object exists continuously even when out of sight and remains in the same place. This is closely related to the development of an infant's ability to represent the existence of the "unseen" object when it is hidden. According to the hypothesis, 7- to 11-month-old infants have not yet reached such a conceptual understanding of objects, and cannot represent where the transferred toy is hidden.

There have been many studies and variations of the A-not-B task that have suggested different interpretations in terms of representational ability, spatial coding, and so on (e.g., Marcovitch & Zelazo, 1999; Munakata, 1998). Typically, the error is attributed to the immaturity of a cognitive subfunction or brain area. The Dynamical Systems approach, however, questions this attribution. The perseverative error also occurs, for instance, when a target object is always visible, that is, when no object is hidden in the task (Smith, Thelen, Titzer, & McLin, 1999), so that factors other than the cognitive inability to represent an "unseen" object must come into play. The pose of the infant during the task matters: Infants were initially trained to reach to the "A" location while sitting on their mother's lap, but then were supported to stand on their mother's lap when the toy was hidden at "B." These infants no longer made the A-not-B error (Smith et al., 1999). This result suggests that the infant's searching error is derived from a visuo-motor bias for a specific location that has been built up and strengthened by repeatedly watching (vision) and reaching (motor) to a cued location at which the experimenter repeatedly showed an attractive toy.

The Dynamical Systems approach takes into account what infants perceive and do on each trial in the A-not-B task, and how their experience in earlier trials impacts behaviors in later trials. That is, while the typical interpretations rest on "what infants know" at some age, the Dynamical Systems account rests on "what infants do" in real time (e.g., Spencer et al., 2006; Thelen, 2000b; Thelen et al., 2001). By shifting the focus from a purely cognitive one to one involving perception and motor activity, the Dynamical Systems approach aims to reveal how cognition emerges from sensory-motor activity.

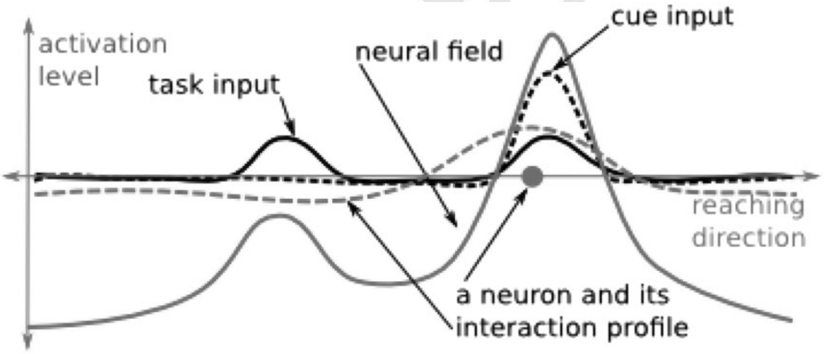
Simulating neural dynamics of the A-not-B task

The Dynamical Systems account of the A-not-B task and many of its variations provides a way to think about how multiple factors are integrated in real time to create a reaching decision (Diedrich, Highlands, Spahr, Thelen, & Smith, 2001; Diedrich, Thelen, Smith, & Corbetta, 2000; Smith et al., 1999). This lends itself to a formal mathematical framework using Dynamic Field Theory (Erlhagen & Schöner, 2002; Kopecz & Schöner, 1995; Thelen et al., 2001). This framework is derived from mathematical models of how neurons cooperate in large populations (Amari, 1977; Wilson & Cowan, 1972, 1973). The power of neural field models is that they provide an account of how macroscopic behavior that we observe in experiments can be linked to the activity of neural populations. Figure 4 illustrates the basic mechanisms of neural field dynamics.

For the A-not-B task, a neural field represents reaching direction: the continuous spatial dimension ranging from leftward locations to rightward locations. The distribution of neural activation in the field captures the tendency to reach in a particular direction; higher levels of activation imply a higher probability of that direction being realized in motor behavior. Activation is induced in real time from perceptual inputs and recent memory. However, activation is integrated in a nonlinear manner by the field: If the activation at some sites passes the firing threshold, then these sites excite their neighbors (neurons that are tuned to similar reaching directions) and suppress activation of far away neighbors: neurons that are tuned to very different reaching directions. When this happens, the field builds a localized activation peak: a decision to reach to “A” or to “B.” These simple neural mechanisms provide the basis of cognitive functions that underlie detection and selection decisions, stabilization of decisions, and long-term memory formation (Thelen et al., 2001; Schöner, 2008 for details).

When a dynamic activation field creates and maintains a peak of activation that represents a motor decision and is followed by an action, a motor memory trace is laid down. This so-called memory trace preactivates sites that have previously been active. The relatively small amount of preactivation is sufficient to bias selection decisions on subsequent trials, inducing the system to make similar decisions in similar contexts. Such a memory trace essentially accounts for the A-not-B error. The memory trace models what is known as Hebbian learning in the neuroscience literature: inputs and actions are associated, and repetitions strengthen the association.

These mechanisms explain infant behavior in the A-not-B task (Thelen et al., 2001). The two hiding locations provide a task input that is persistent but weak. The cuing of a location, for instance, hiding a toy, provides a strong transient input that gradually decays given a delay. During the training trials (“A” trials), location “A” will likely be selected because all inputs support “A.” Each reach toward “A” will generate some motor memory for “A.” This memory is in competition with the cue at the new location “B” during the test trial (“B” trials). Which side wins depends on where the activation is higher when reaching is allowed after the delay. In experiments, infants make more A-not-B errors the longer the delay is; in addition, older



The x-axis represents the reaching direction from left to right. The y-axis represents the activation levels of the neural field and of inputs. Positive values are plotted above the x-axis and negative, respectively, below. Negative field activation indicates how much input is needed before the threshould is reached when a neuron becomes active and “fires” to influence other neurons in the field. In the A-not-B context, task input (the two hiding locations, solid black curve) and cue input (the presentation of the toy, dashed black curve) induce activation peaks in the neural field (solid gray curve). Of the two peaks one is above and one is below threshold (x-axis). The field activation does not merely reflect the sum of inputs, but is also internally modulated due to nueral interactions. Neurons that are activated above threshold do add positive activation to nearby neurons and inhibit distant neurons, as exemplified for one neuron (gray circle) by its interaction curve (dashed gray curve). The final shape of the neural field results from the sum of all current inputs and neural interactions.

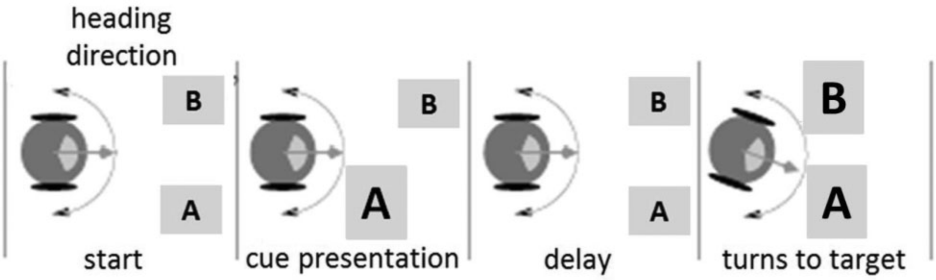
Figure 4 Basic conventions and principles for neural field dynamics.

infants tolerate longer delays before they make the error (Diamond, 1985).

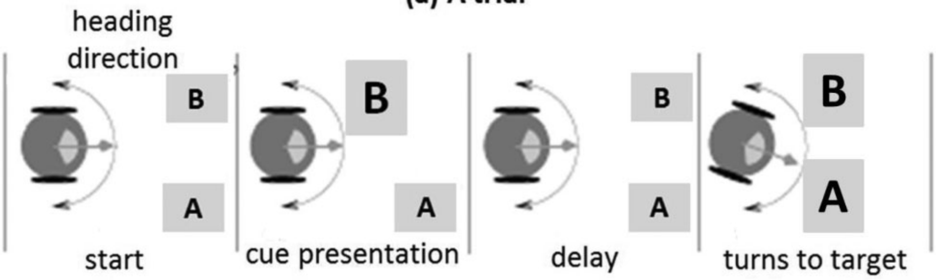
In their account of the age and delay effects, Thelen and colleagues proposed that neural interactions strengthen over the course of development (Thelen et al., 2001). As the delay increases, the cue activation at "B" decreases, making a reach more likely to be biased by the memory at "A." Stronger interactions may maintain the cue activation for a longer period, which allows infants to tolerate longer delays before they make the A-not-B error. Moreover, the model explains why details of the experimental procedure matter. For instance, the error can be reduced if the task input supports "B" (Diedrich et al., 2001) or if the cue is made more attractive (Clearfield, Diedrich, Dineva, Smith, & Thelen, 2009).

Re-enacting the A-not-B task with an autonomous robot

A critical aspect of the Dynamic Field Theory is that it explains how cognitive decisions can be coupled to sensory-motor systems. This allows for an implementation on a robot that acts autonomously (Dineva, Faubel, & Schöner, 2007; E. Dineva, personal communication, June 2013). Colored flags of different sizes are used to present inputs to the robot in a manner consistent with the timing of inputs in the A-not-B task. Two small flags specify the task input and a larger one is presented for cuing. Figure 5



(a) A trial



The youngest robot in typical A (top row) and B trials (bottom row). Each trial begins with the robot facing two small task flags at the far end for 1 second (first column: start). Then a cue flag is presented for 4 seconds (second column: cue presentation) at the respective location A (top) or B (bottom). During a 3 seconds delay, the robot faces again the far flags (third column: delay). At the end of the delay, both task flags are moved to close to the robot (last column: response). This initiates a response which for the young robot is typically a turn to the A location on both trials. The curved double arrow indicates the span of heading directions, the robot's possible responses.

Figure 5 Schematic description of the robotic replication of the A-not-B error task.

sketches one “A” and one “B” trial in the robotic version of the task.

First, six “A” trials are presented, then two “B” trials. Each trial starts with the robot facing two distant task flags. After that, a cue flag is presented at “A” in the “A” trials or at “B” in the “B” trials. The cue induces a peak in the robot’s neural field, but it decays during the subsequent delay. Next, flags are placed close to the robot and a new peak is created. The peak location defines an attractor for the robot’s heading direction. As a response, the robot turns to the selected location. This behavior creates a motor memory for the selected location. During the “A” trials the field typically selects location “A” because of residual cuing activation and training trials where the “A” task flag is placed slightly closer; then after the initial turns to “A,” the motor memory that was created for “A” further biases reaches toward “A.”

The robot usually has a strong motor memory for “A” when the “B” trials start. This memory is the deciding factor in causing a turn to “A” on the B trials, as the cuing activation for “B” virtually vanishes during the delay. The robot thus typically makes A-not-B errors like those of young infants. Different experimental contexts can be realized by varying the delay or the sizes of the flags. This directly translates to different distributions of input activation. For instance, a larger flag will create a stronger input, and thus a stronger (more stable) peak in the neural field that can persist over longer delays.[4] In addition, by increasing the strength of the neural interactions, the simulated “age” of the robot can be increased. The “older” robot is able to maintain activation over longer periods.

The robotic implementation demonstrates two critical aspects of the Dynamical Systems approach. First, the implementation is proof of principle as to how autonomous behavior may emerge from the dynamic coupling of perception/action and cognition in real time and in a real environment. The realization of stable states of the behavioral dynamics is the key step toward emergence of behavior. Second, the macroscopic dynamics of behavioral patterns derive from the microscopic dynamics of neuronal interactions. The neuronal activation self-organizes in stable patterns by integrating perceptual inputs and memory input from recent behavior with cooperative interactions among the neurons. This elegantly proves that perception (perceptual input)/action (behavior) and embodied cognitive aspect (memory input from recent behavior) are seamlessly interrelated and then generate new patterns. Thus, the robotic implementation illustrates also how the Dynamical Systems approach goes beyond the ecological approach: the neural processes from which behavior emerges are explicitly addressed and accounted for in the Dynamical Systems approach, while ecological psychology has primarily focused on describing the end-result of these processes.

Elaborating situation: Infants encounter complexities in everyday life

As shown, the A-not-B task has been a central focus of many studies because it illustrates how the perceptual, motoric, and cognitive abilities of young children (and robotic devices!) all come together to create behavior. However, some researchers might think that the setting of the A-not-B task is too simple (and/or restricted) to be able to reveal “general” mechanisms and to illustrate the dynamic nature of cognitive development. Young children encounter in everyday life environmental settings and objects with much richer perceptual and motor structures than the canonical A-not-B situation, and they have to cope with more complex task demands.

Here, we introduce one more example of our projects in which we attempted to make the A-not-B task more realistic by using attractive and complex objects affording multiple possibilities of playing (Maruyama, Schöner, Spencer, Whitmyer, & Thelen, 2007). By doing so, we show how the scope of the Dynamical Systems account, its modeling concepts, and the

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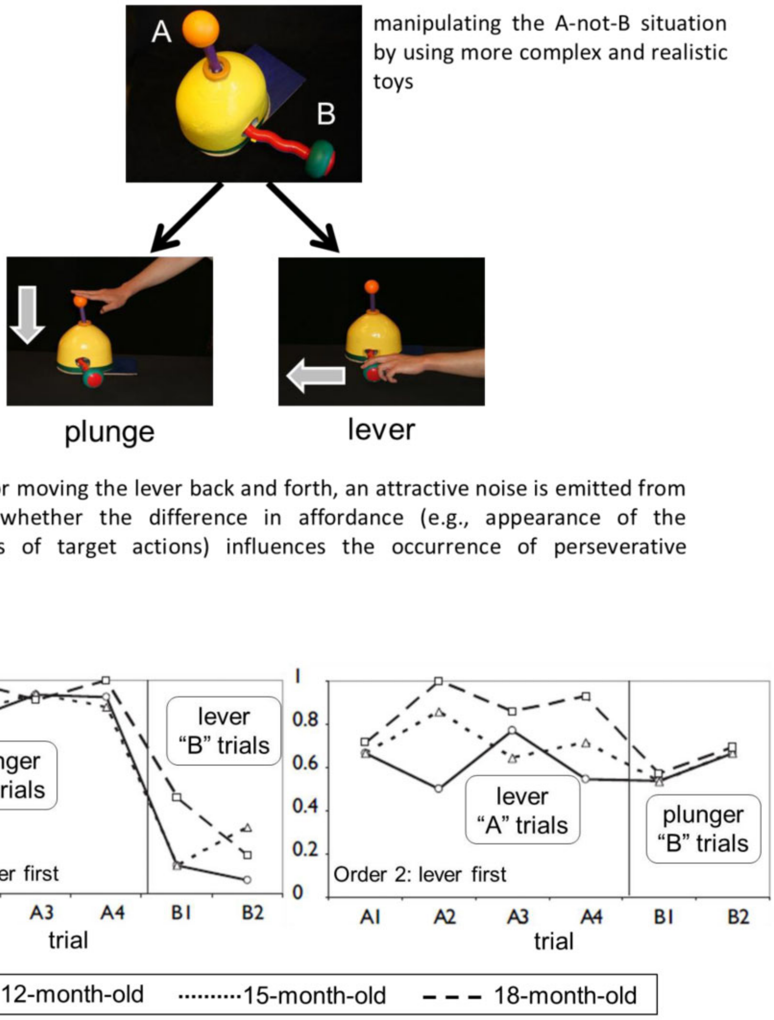
[4] This is a simplified model of motivation: stronger activation creates more reliable representations that are resistant against competing inputs and that can overcome a long delay. This has also been shown for infants (Clearfield et al., 2009).

robotic simulation of the A-not-B study can be applied to more naturalistic scenarios.

We conducted a study of children aged 12, 15, and 18 months in which we used a set of painted toys that produced interesting noises when one of two manipulanda on each toy was appropriately manipulated ("Plunger-Lever" toy: Figure 6). The manipulanda had different features and were asymmetrically attached to the toy: a small ball at the upper end of the plunger and a knob at the end of the lever. The toys in the set were identical in appearance but differed in the action needed to produce attractive noises. Critically, for any one toy, only one action was possible in any given trial, although two salient manipulanda were visible.

The procedure of the study was analogous to the canonical A-not-B paradigm. The first four trials were "training": the experimenter demonstrated one of the target actions on one manipulandum (the "A" action). After a short delay, the experimenter pushed the toy toward



manipulating the A-not-B situation by using more complex and realistic toys

By pushing the plunger or moving the lever back and forth, an attractive noise is emitted from the toy. We observe whether the difference in affordance (e.g., appearance of the manipulanda and types of target actions) influences the occurrence of perseverative responses (footnote 5) .

Colour online, B&W in print

7 8

Figure 6 The choice task analogous to A-not-B using a complex toy and the occurrence of a perseverative response.

the child, enabling the child to interact with the toy. After the "training" trials, the experimenter demonstrated in two "test" trials the alternative action on the other manipulandum (the "B" action). The experimenter used a visually identical toy, which they had actually switched between the "A" and "B" trials. On the new copy, only the "B" action produced a sound; the "A" action no longer did. After a short delay, the child was again allowed to interact with the toy. We coded whether children imitated the demonstrated action or switched to the alternative action and, in particular, examined whether children showed perseverative bias toward the actions demonstrated in the training trials. That is, for the test trials ("B" trials), returning to "A" was coded as a perseverative error, and switching to "B" was coded as an imitative (nonperseverative) behavior. We analyzed children's decision making processes in the task and how children's decisions were subject to interactions among multiple factors including object affordances, task details, and motor memories.

The results showed that younger infants were generally more perseverative than older infants. Note that even the youngest age group of the subjects in our experiment (12 months old) was a little older than the age at which perseverative responses are expected to appear in the canonical A-not-B task (generally at approximately 7–11 months old). The observation of perseveration in this task compared to no perseveration in the canonical task indicates that motor selection decisions are affected by behavioral context. This "shifting of (cognitive) ability" is strong evidence that cognitive development does not follow a hard-wired program but flexibly changes with task context.[5]

Furthermore, the occurrence of imitative responses was sensitive to the order of the demonstration and the salience of the target actions/manipulanda that seemed to be related to the child's perception of the difference in affordance between the target actions. We interpreted these results in light of Dynamic Field Theory, arguing that children's responses arose from real-time interactions among multiple factors. Perception of the different affordances of possible actions on the toys, the salience (i.e., attractiveness and/or complexity) of the toys, and children's action repertoires are integrated over multiple time scales, that is, in real time, and across trial-to-trial experience with the task. This study thus supports the Dynamical Systems account of the A-not-B task and extends it beyond the canonical A-not-B situation toward more realistic (ecological) situations.

Concluding remarks

In this review paper we emphasized the seamless link between sensory-motor activity and the development of higher cognitive abilities, highlighting current directions in the Dynamical Systems approach including formal mathematical modeling and robotics, but also discussing ideas from the ecological perspective of development. Our reinterpretation of the prevailing assumptions about Piaget's A-not-B error suggests that intellectual development emerges from complex interactions among multiple elements, such as the perception of object affordances and motor history built up through bodily experiences. The continuous interaction between perceptual and motor activities across multiple time scales is essential for the emergence of new patterns. That is, the

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[5] The results described here are based on a part of our study (manuscript in preparation). In the original experiment, we used two toys appealing different affordances ("plunger and lever," shown in Figure 6, and "hinge and button"). We ran a mixed-design ANOVA on the data of both toys with Age (12-, 15-, and 18-month-olds; 85 infants total) and Condition (presentation orders of actions on each toy) as between-subjects factors, and Toys and Trials ("A" & "B" trials) as within-subject factors. The ANOVA revealed a significant main effect of Age, $F(1, 79) = 4.775$, $p = .011$. Post hoc tests (Tukey's HSD) showed significantly less imitation in each of the two younger age groups (12- and 15-month-olds) relative to the 18-month-olds ($p < .05$), but no significant difference between the 12- and 15-month-olds' performance. In addition, there were a significant Toy by Trial by Condition interaction, $F(1, 79) = 19.350$, $p < .001$.

environment, body, and nervous system are all coupled, nested, and mutually influenced over time (Thelen, 2000b).

Note that, although we have contrasted our viewpoint with Piaget's perspective, we do not mean to deny or belittle the important contributions Piaget has made to the understanding of development. In fact, Piaget was a pioneer in recognizing the fundamental role sensory-motor experience plays in cognitive development. We concur with this insight. However, Piaget's views have often been interpreted to imply a separation of sensory-motor activity from cognition. Dynamical Systems thinking suggests that cognition and sensory-motor activity remain tightly coupled (Thelen, 2000b; Thelen et al., 2001; Thelen & Smith, 1994).

Cognitive development is, thus, not simply about the acquisition of "static" catalogues of knowledge. By continuously perceiving and acting in our environment, we are dynamically updating the current state of our cognitive system. Indeed, as shown in the robotic replication of the A-not-B error, the current state of the cognitive system is shaped by multiple influences on multiple time scales. That is, cognition reflects the dynamic blending of previous experience and perceptual/motor activities in the here-and-now, leading the system into new states.

This might be the very driving force of development. For instance, consider the following "mountain stream metaphor," which illustrates the complex ways in which change may emerge through time:

> At some places, the water flows smoothly in small ripples. Nearby may be a small whirlpool or a large turbulent eddy. Still other places may show waves or spray. These patterns persist hour after hour and even day after day, but after a storm or a long dry spell, new patterns may appear. Where do they come from? Why do they persist and why do they change? (Thelen & Smith, 2006, p. 263).

Patterns of water flow are changeable in unpredictable ways due to geological and weather influences. The flow patterns we observe now are not preprogrammed but emerge from complex and elastic interactions among many factors. Any of the expressed patterns inevitably contains a history of cycles of pattern formation and reformation which has been accumulated (and is accumulating) in succession from the past to the present. You can see the sharp contrast between this metaphor and the pervasive view that development emerges from a primary cause (i.e., brain maturation) on a single time scale (i.e., a linear developmental course).

The examples provided here including the infant studies, the mathematical formulation of a model of the A-not-B error, and its robotic implementation, point to the embodied and dynamic nature of cognitive development and its concrete mechanisms. More recent work has extended this flavor of Dynamical Systems approach. Dynamic neural fields have been shown to capture central properties of habituation and memory formation in infancy (Perone & Spencer, 2013; Schöner & Thelen, 2006), as well as of executive function (Buss & Spencer, 2014) and word learning (Samuelson, Smith, Perry, & Spencer, 2011) in early development. Critically, the attention that researchers have given to the emergent mechanism of cognitive ability coupled to bodily activity in a behavioral context (i.e., embodiment) is not limited to the field of developmental psychology. Interest has spread to interdisciplinary research areas, such as robotics, where the challenge is to develop artificial intelligence (Clark, 1997) and to construct cognitive developmental robotics (Asada et al., 2009). Pfeifer and Bongard (2007) have clearly characterized this movement: "the body is required for intelligence." We believe that the trend is toward formulating a grand theory of development (Spencer et al., 2006).

Although the dynamical systems and ecological views described herein have been successfully applied across multiple domains, there are several current limitations of these approaches (for discussion, see Spencer, Austin, & Schutte, 2012). To date, the Dynamical Systems approach has had a relatively modest impact on developmental behavioral neuroscience.

Recent efforts to extend Dynamic Field Theory to cognitive neuroscience are a promising step toward overcoming this limitation (see, e.g., Buss & Spencer, 2014; Spencer, Barich, Goldberg, & Perone, 2012), but a great deal of work remains.

More recently, Buss and colleagues demonstrated empirically how neural and behavioral dynamics are linked. They used the modern imaging techniques of NIRS (Buss, Fox, Boas, & Spencer, 2014) and fMRI (Buss, Wifall, Hazeltine, & Spencer, 2013) to estimate neuronal activation patterns, which can be mapped onto the Dynamic Neural Fields, and that also account for behavioral data. No other theory has yet provided a coherent system that explains both neuronal and behavioral patterns within an unified framework. Dynamical systems thinking has successfully been applied into the design of robotic vehicles (Agrawal, Galloway, & Ryu, 2012; Galloway, Cope, Gopez, Cope, & Braucht, 2013; Galloway & Logan, 2013) to increase the behavioral repertoire of children with mobility deficits, such that these children can more strongly engage in a perception/action loop and thus show less cognitive impairment than do their peers (Galloway, Ryu, & Agrawal, 2008). In addition, Perone and Spencer (2013) investigate how looking behavior can influence learning, and propose how learning can be enhanced for preterm infants. Further, beyond childhood, Kunnen (2012) has begun to expand applicable fields of the Dynamical Systems approach to adolescent development, such as identity development in adolescence and the emergence of adulthood. Overall, however, the Dynamical Systems approach has not had a major impact on clinical and translational work in developmental science. This is unfortunate given that there is a natural synergy between Dynamical Systems concepts and the study of individual differences. At the heart of the Dynamical Systems approach is the notion that each child carves out a unique developmental trajectory over time. One key future direction, therefore, is to explore what Dynamical Systems concepts might have to offer developmental clinical science.

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