# Change occurs when body meets environment: A review of the embodied nature of development

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# Change occurs when body meets environment:

## An essay on the embodied nature of development

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**Abstract**

The purpose of this paper is to outline challenges of psychological research on the mechanism 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 the dynamic systems account and relevant views such as the ecological approach to perception and action, and cover topics ranging from early motor skills, and goal-directed locomotion, and to higher cognitive development. The point 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 reenact the situatedness and temporal structure of the decision making processes of human infants by using an autonomous robotic device. We conclude that insights from a broad spectrum of studies looking into the embodied nature of adaptive behavior, cognition and autonomous robotics are making a profound contribution to uncovering the emergent mechanism of intellectual and bodily activity throughout development.

**Keywords**: development, embodiment, dynamic systems approach, perception and action, ecological approach

## Introduction

How does an appropriate behavioral pattern emerge in a situation changing moment by moment? How do we learn skills for goal-directed activities that meet task demands? This remains one of the enduring questions of "development" despite a variety of research that has tried to reveal its mechanisms. The primary purpose of this paper is to review the challenges of developmental psychology and related fields as regards the foundation of human development, by focusing on the mechanism of emergence—how a new pattern arises from the interaction of an organism with its environment in real time.

We feature current directions in the dynamic systems approach (Thelen & Smith, 1994) and the ecological approach to perception and action (Gibson, 1979; Gibson, 1988). We will cover topics ranging from early motor skills (e.g., alternative stepping) and goal-directed locomotion to higher cognitive development (e.g., perseverative response in a task analogous to Piaget's A-not-B error [Piaget, 1954]), and we will also present mathematical models and the replication of human behavior by an autonomous robotic device. The studies that we have chosen to present here are evidence *against* the prevailing theory that the occurrence of developmental changes 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 affordance of the environment/object, and the behavioral history on multiple time scales from a moment in time to an organism's whole life. This "context-dependency" of development and the role of sensory-motor aspects in forming a new pattern are evidence that we should re-think the mechanisms driving development in light of the dynamic systems view (Thelen & Smith, 1994; Thelen, et al. 2001). Because our own works (mathematical modeling, robotic agents, and behavioral studies with infants) capture the contextual and temporal structure of decision making when choosing between two targets which have different perceptual values, we think that they are reasonable demonstrations that cognitive processes link to sensory and motor aspects. We also expect that a successful robotic replication of human data would lead to a new understanding on how the emergence of cognitively guided behavior depends on the structure of the nervous system, the properties of the environment, and the behavioral history of the agent.

We conclude that the insights from a broad spectrum of research and techniques for experiments looking into the

assembly of adaptive behavior and cognition and autonomous robotics are beginning to uncover the emergent mechanisms of cognitive activity and the nature of "embodiment". This is in accord with the contemporary perspective of cognitive development that cognition (our knowledge) is inseparable from *non*-cognitive processes of perceiving and acting, and is in sharp contrast to traditional view that separates cognitive processes from sensory-motor processes (Smith & Sheya, 2010). We hope this paper will enable readers to catch up with the paradigm shift in developmental studies and see how essential the real time dynamics of embodiment (seamless integration of perception, action and cognition in real time) is for the occurrence of dexterous changes in behavioral and cognitive ability. We believe that what we will illustrate here has rich implications for developmental studies and various research fields related to the science of intelligence (artificial intelligence, robotics, and so on).

## 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, pp.12)— This quote is from a book, "*A Dynamic Systems Approach to the Development of Cognition and Action*" authored by Thelen and Smith, who have enterprisingly applied principles of nonlinear dynamics ("chaos theory") to the field of developmental psychology. Their work is a major breakthrough in answering the hard question about how organisms change over time. They have challenged classical theories of development that have 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). It is an initial step toward an understanding of emergent mechanisms of developmental changes in light of the fundamental link between organisms and their environment.

### Body meets environment

The first example is the "mystery" of baby's stepping movement that appears at birth. It is generally observed that most babies appear to move their legs rhythmically and alternatively when held upright over a flat surface. This stepping behavior is usually called the stepping reflex and is counted as one of a variety of newborn primitive reflexes. It looks very much like a well-coordinated "walking" behavior. At around two months of age, however, this movement

suddenly disappears (Figure 1: panel[a]), but it *re*-appears at around 1 year old when a baby is about to walk independently. Here, we encounter a 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 a subcortical output (a genuine reflex) and, as the cerebral cortex matures and differentiates, it is inhibited until it disappears. Then, through a period of brain reorganization, the stepping movement reappears in a new form, as a component of voluntary walking (Zelazo, 1983; Cole, et al. 2005).

In contrast to the accepted view, Thelen and her colleagues described a very different picture. In longitudinal studies of physical and behavioral development in infants, they focused on the relationship between individual differences in the rate of gaining weight and the period in which the stepping behavior disappears and 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 her 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, et al. 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 infants' legs and their muscle force. The researchers further demonstrated that the appearance of the stepping behavior could be controlled by adding some contextual manipulation: they held infants around 7 to 10 months old, whose stepping behavior had not reappeared yet, on a treadmill machine and had them stand upright (Thelen, 1986). When the machine was turned on and the belt started moving, the infants showed well-coordinated leg movements, and they adjusted the rate of their stepping to the speed of the moving belt (Figure 1: panel b).

========== Figure 1 around here ==========

These data show that the emergence of movement patterns in infants is subject to contextual influences, implying that the developmental path is not linear and, further, that brain maturation is not the single cause controlling developmental change. This viewpoint is straightforwardly illustrated by Thelen and Smith: "…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). Development is a product not of a program, but of complex interactions among multiple factors including the agent's body (sensory-motor foundation), environmental and task constraints, and so on. This radical shift in thinking about developmental changes motivated Thelen and Smith to apply the ideas of nonlinear dynamics to developmental psychology, and this effort has resulted in a new theoretical framework known as the dynamic systems approach to development.

## Dynamic explanation of a goal-directed action

The preceding section introduced the dynamic systems viewpoint with reference to studies on a newborn baby's stepping behavior, a repetitive and seemingly involuntary movement (footnote). However, 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 grab it. It is known that reaching and grasping behavior in healthy infants appears around four months of age, and this milestone of behavioral development is frequently used as a diagnostic sign of normal development because the period of its appearance is reliably regulated (Rochat, 2001). Actually the developmental path of reaching behavior in infants is quite variable, which contrasts with the "universal" picture often assumed to be the case. This has shed new light on the developmental course of the behavior (Thelen, et al. 1993; Thelen, et al. 1996). Thelen and her 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 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 and active perception and control of the ongoing motor behavior (e.g., online monitoring of the arm movement, changes in posture and so on) in relation to the location of the target object. In this sense, the reaching behavior is organized by integrating the infant's intention (i.e., motivation to gasp the toy) with the unique constraints of an individual's body dynamics. Although healthy infants eventually learn to reach in similar fashion, the processes underlying their success are not universal but rather various and individualistic (Spencer, et al. 2006). This result supports the idea that the intrinsic dynamics of an agent's body play a crucial role in the achievement of goal-directed actions.

The next example from the literature is on young children's ability to perceive possibilities for action (i.e., affordance) in the context of goal-directed locomotion focusing on how children perceive and utilize tools around them for adaptive locomotion (Berger & Adolph, 2003). In the study, healthy 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). The width of the bridge, ranging from 12cm to 72cm, and the presence/absence of the handrail were systematically manipulated. The results reflected the judgments of the toddlers: when the widest bridge (72 cm) was presented, they ran over on the bridge without hesitation (in fact, they spent a minimal amount of time for exploratory behavior on the platform) and nearly ignored the presence of the handrail. However, on narrow bridges (12 cm -24 cm), they attempted to walk *only* when the handrail was available, and they avoided crossing when the handrail was absent. In concert with the infants' choices of locomotion patterns, the time spent in exploratory behavior got longer when they encountered the narrow bridges.

========== Figure 2 around here ==========

The point of this result is that the behavioral decision making of the toddlers as to whether they cross the bridge or stay on the platform comes from their active exploration of the possibility to realize a safe crossing and that was

essentially related to perception of the environmental changes in the bridge width and of affordance of the handrail as a tool able to enhance the toddler's body balance. In this sense, 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), and they flexibly attuned their behavioral patterns in proportion to the changes. This study thus indicates that, by actively coupling perception of their own motor ability with perception of their behavioral context, toddlers made real-time, dynamic decisions that came not simply from *knowledge* that had been learned and stored in advance, but from *learning* that was continuously updated during the task.

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

As we illustrated above, disturbances in the environmental settings (e.g., submerging in the water or with/without the handrail) lead children to (re-)organize their behavioral patterns. Moreover, the intrinsic dynamics of limbs motivate individualistic solutions for possible and effective actions to achieve a goal in reaching tasks (e.g., reaching and grasping an attractive toy). These examples have qualified that the immediate sensory-motor experiences and an agent's active engagement in a task play a significant role in the child discovering the "values" or "meaning" of an environment and task and result in an adaptive behavioral solution in a context. Moreover, the execution of certain behavioral patterns allows children to perceive new and/or different opportunities for action. That is, the relationship between perceiving and moving is reciprocal and cyclic (Gibson, 1979; Gibson, 1988). James J. Gibson, a pioneer of the ecological approach and who elucidated the concept of *affordance*, focused on this perception/movement cycle: "So we must perceive in order to move, but we must also move in order to perceive" (Gibson, 1979). 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 as "an integral part of the ensemble of all our experience" (Thelen, 2000a).

But we need to go further — how does perceiving and moving in an environment link with higher cognition, which has been thought of as being distanced from the immediacy of the sensorimotor domain? Theories of cognitive development have long assumed that as our mental activity becomes abstracted with development, perception and movement are gradually set aside and become mere "bystanders" (Smith & Sheya, 2010; Thelen, 2000b). In what

follows, we shall review Thelen, Smith, and colleagues' empirical evidence of the inseparability of cognition from perception and bodily experience. They paid special attention to the "A-not-B error" paradigm of Jean Piaget (1896-1980), a developmental psychologist who has had a profound impact on studies on the origin of human thought (epistemological development). In the following, we outline the paradigm and its canonical interpretation. Then, by contrasting the canonical view with insights from recent studies on the A-not-B paradigm including our own work, we argue that it is necessary to *re*-interpret the traditional perspective in light of dynamic systems and ecological views.

## Piaget's "A-not-B" error and challenges to the prevailing interpretation

The "A-not-B error" (Piaget, 1954) is a perseverative error made by children aged seven to eleven months when they engage in a task of searching for a hidden toy (Figure 3). In the task, the experimenter presents and hides a toy at location "A" and, after a short delay, infants are allowed to reach toward that location and discover the toy there. After repeating this procedure a couple of times, the experimenter switches the location 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, she perseveratively reaches toward the original location A. This perseverative tendency to reach toward the original and erroneous location is called the "A-not- B" error. It occurs even though the infant watches the whole sequence of events in the task.

========== Figure 3 around here ==========

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 if no external force is given, an object at rest continuously exists and remains in the same place. This concept is closely related to the development of an infant's symbolic ability to represent the existence of the "unseen" object when it is hidden. Seven to eleven-month-old infants have not yet reached such a conceptual understanding of objects, and cannot represent where the transferred toy is hidden. Because they lack this cognitive ability, infants believe that the toy continues to exist at the original location where they reached before, even after they watch the toy being hidden at the other location.

There have been many studies and variations on 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 regarded as reflecting the underdevelopment of a cognitive sub-function or brain area. The dynamic systems approach however questions whether the A-not-B error is exclusively due to immature cognitive sub-functions. There is evidence, for instance, that the same perseverative error occurs when a target object is always *visible*, that is, when no object is hidden in the task. This result indicates that infant's searching error does not come from lack of cognitive ability to represent "unseen" object (Smith et al. 1999). Further, it has been shown that shifting the posture of infants during the task has a big impact on the occurrence of the perseverative error: infants *sitting* on their mother's lap were initially trained to reach to the original location, and after that, the researcher had the infants stand on their mother's lap with support. After the toy was transferred to a new location with *standing* infants, the occurrence of the A-not-B error significantly decreased (the standing infants tended to correctly reach on both A and B trials) (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. This bias cannot be easily overcome by the new perceptual input (experimenter's cues at the new location), but it can be overcome by a shift in the motor context.

The core of the dynamic systems approach goes beyond canonical interpretations that ascribe the cause of the A-not-B error to the infant's cognitive immaturity. The dynamic systems view 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 dynamic systems account rests on "what infants *do*" in real time (e.g., Thelen et al. 2001; Spencer, et al. 2006; Thelen, 2000b). By shifting the focus from the purely cognitive to one involving perception and motor activity, the dynamic systems approach aims to reveal how cognition emerges from sensory-motor activity. In the following sections, we expand on this account. First, we present a mathematical model that describes the real time dynamics of correct and perseverative responses in the A-not-B paradigm. The model uses neural activation mechanisms and stays close to perception-action systems. We show this directly in a subsequent section by implementing the model on an autonomous robot. This demonstrates directly that

the A-not-B account captures the reciprocal integration of body and mind, that is, how thinking and decision-making can be embodied in context.

### Simulating neural dynamics of the A-not-B task

The dynamic systems account of the A-not-B task and many of its variations provide a way to think about how multiple factors are integrated in real time to create a reaching decision (Smith et al. 1999; Diedrich, et al. 2001; Diedrich, et al. 2000). This lends itself to a formal mathematical framework using Dynamic Neural Field Theory (Thelen, et al. 2001; Erlhagen, et al. 2002). This framework is derived from the mathematics of how neurons cooperatively operate in large populations (Amari, 1977; Wilson & Cowan, 1972; Wilson & Cowan, 1973). 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 mean higher probability. Activation is induced in real time from perceptual inputs and recent memory. However, the activation is integrated in a non-linear 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 function of detection and selection decisions, stabilization of decisions, and long term memory formation (Thelen, et al. 2001). The detection decision is whether an input is strong enough to exceed the threshold for neural interactions to create a peak. This peak builds up where the activation is strongest, and its location represents the location where to reach. A selection decision happens when multiple strong inputs specify several reaching options; the field then will select a single location by creating a single peak. If some inputs are closer than their excitation range, their activation will merge into a single peak. If they are farther apart, the peak that forms first will suppress competing inputs by means of global inhibition. How well a peak is stabilized depends on the strength of the neural interactions. Stronger interactions suppress competing inputs and prevent decay when the initiating input is no longer available. Finally, when neurons create and maintain a decision that is followed by an action, a persistent motor memory trace is created. This trace provides the input that makes a similar

decision likely to reoccur given a similar context. This process models what is known as Hebbian learning in the neuroscience literature.

The above 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. If reaching is allowed immediately after the cue while its activation is still strong, the cued location will likely be selected. During the delay, the cue activation gradually decays and loses its impact on reaching. During the training trials (A trials), location A will likely be selected because all inputs support A (note that in the few initial trails, the toy at A is placed close to the infant and thus provides a somewhat stronger input). 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 infants tolerate longer delays before they make the error (Diamond, 1985).

In their account for the age and delay effects, Thelen and colleagues proposed that neural interactions strengthen during the course of development (Thelen, et al. 2001). As the delay increased, 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; eventually interactions are strong enough for the cue peak to be self-sustaining and persistent, always leading to correct responses. Moreover, like the degree of stabilization, the experimental details are also important. The dynamic neural field theory proposes that changes to task and cue inputs directly influence the activation levels at A and B. The theory explains, for instance, how the error can be reduced if the task input supports B (Diedrich, et al. 2001) or if the cue is more attractive (stronger) (Clearfield, et al. 2009).

### Reenacting the A-not-B task with an autonomous robot

A critical aspect of the dynamic neural 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, which we are currently testing (Dineva, et al. 2007; Dineva, et al. in preparation). Colored flags of different sizes are used to present inputs to

the robot in a consistent manner 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 4 sketches one “A” and one “B” trial in the robotics task.

========== Figure 4 around here ==========

First, six A trials are presented, then, two B trails. 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 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. In addition, the age of the robot can be ‘increased’ by increasing the strength of its neural interactions, which allows the robot to maintain activations over longer periods.

### Elaborating situation: Infants encounter complexities in everyday life

The A-not-B task has been a central focus of many studies because of its profound illustration of the perceptual, motoric and cognitive abilities of young children. 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 illustrate the dynamic nature of cognitive development. In everyday life, young children encounter environmental settings and objects having much richer structures than the A-not-B situation, and they have to cope with more complex task demands. Thus, in order to show the scope of our viewpoint, we must go further. Here, we present a brief outline of our projects

(Maruyama, et al. 2007a; Maruyama, et al. 2007b; Maruyama et al. in preparation) which are exploring children's decision making processes in an object manipulation task and how children's decisions are subject to interactions among multiple factors including task details and motor memories.

As an example, 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 the manipulanda on each toy was appropriately manipulated ("Plunger-Lever" toy: Figure 5). 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, though two salient manipulanda were visible.

========== Figure 5 around here ==========

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 ("A" action on either manipulandum) and, after a short delay, allowed children to interact with the toy. In the next two "test" trials, the experimenter demonstrated the alternative action on a visually identical toy (switching to the "B" action on another manipulandum) and after a short delay, allowed the children to explore. We coded whether the children imitated the demonstrated action or switched to the alternative action and particularly examined whether children showed perseverative biases to 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 (non-perseverative) behavior.

Results showed that the younger infants were generally more perseverative than older infants. Note that even the youngest age group of the subjects in our experiment (twelve months old) was a little older than the age at which the perseverative responses are expected to appear in the canonical A-not-B task (generally around seven to eleven months old), indicating that the subjects' behavioral decision making was affected by the behavioral context. This "shifting of (cognitive) ability" is strong evidence that cognitive development does not follow a hard-wired program but flexibly

changes as the task context shifts.

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 (Thelen, et al. 2001), arguing that a child's responses arose from real-time interactions among multiple factors. Perception of the different affordances of possible actions on the toys, salience (i.e. attractiveness and/or complexity) of the toys, and a child's action repertoires are integrated over multiple time scales, that is, in real time and across trial-to-trial experiences (motor history) in the task. This study supports our dynamic systems account and extends it beyond the canonical A-not-B situation.

## Concluding remarks

The present paper has shed light on the seamless linkage between sensory-motor activity and the development of higher cognitive ability, highlighting current directions in the dynamic systems approach including formal mathematical modeling (with dynamic field equations) and links to the ecological perspective. Our re-interpretation of the prevailing assumptions on Piaget's A-not-B error provide evidence that intellectual development emerges from complex interactions among multiple elements, such as 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 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 deny the important contributions he has made to the understanding of development. In fact, Piaget was the person to recognize the fundamental role of the sensory-motor experiences in infants in subsequent cognitive development. We concur with this insight about the growth of abstract thought. But, in Piaget's interpretation, sensory-motor experiences become mere peripheral things as an agent learns and acquires conceptual knowledge. Consequently, this assumption has brought about a separation of sensory-motor activity from cognition. On this front, we see a critical gap between Piaget's theory (Piaget, 1954) and our dynamic systems view that cognition and sensory-motor activity remain tightly

coupled (Thelen & Smith, 1994; Thelen, et al. 2001; Thelen, 2000b).

Cognitive development is, thus, not simply about the acquisition of "static" catalogues of obtained knowledge. By continuously perceiving and acting in our environment, we are dynamically updating the current state of our cognitive system. Indeed, as shown in earlier section with our robotic replication of the A-not-B error, the current state of the cognitive system is influenced by multiple influences on multiple time scales. That is, cognition reflects the dynamic blending of previous experiences 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" that illustrates the complex ways in which change can 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, pp.263).

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

The examples provided here including a mathematical formulation of the A-not-B error (the dynamic field model) and empirical experiments (robotic replication and infant study) point to the embodied and dynamic nature of cognitive development and its concrete mechanisms. Moreover, other recent studies have taken the implications of the dynamic systems and related them to a broad range of topics, such as the social influences of adults on children's

cognitive performance (Topál, et al. 2008; Spencer et al. 2009) and re-interpretation of the habituation mechanism that has been one of a major paradigm in the developmental studies investigating infants' mental process to detect feature differences between stimuli (Schöner & Thelen, 2006). Furthermore, it has been reported that young children's rate of object completion is strongly related to their "sitting" skills (Soska, et al. 2010). And such, the attention that researchers have on the emergent mechanism of cognitive ability coupled to bodily activity in a behavioral context (i.e., embodiment) is not limited to the field of the developmental psychology. Interest has spread to interdisciplinary research areas, such as robotics, where the challenge is to develop artificial intelligence (Clark, 1997). 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). So, our concluding remark for the reader is that an agent's body continuously encountering its environment drives its development—this may be a clue to the long-lasting puzzle of the emergence of higher intellectual abilities from "an unformed and helpless creature" (Thelen, 2000b; Smith & Thelen, 2003).

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**Footnote**

Thelen & Smith argue 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" (Thelen & Smith, 1994).

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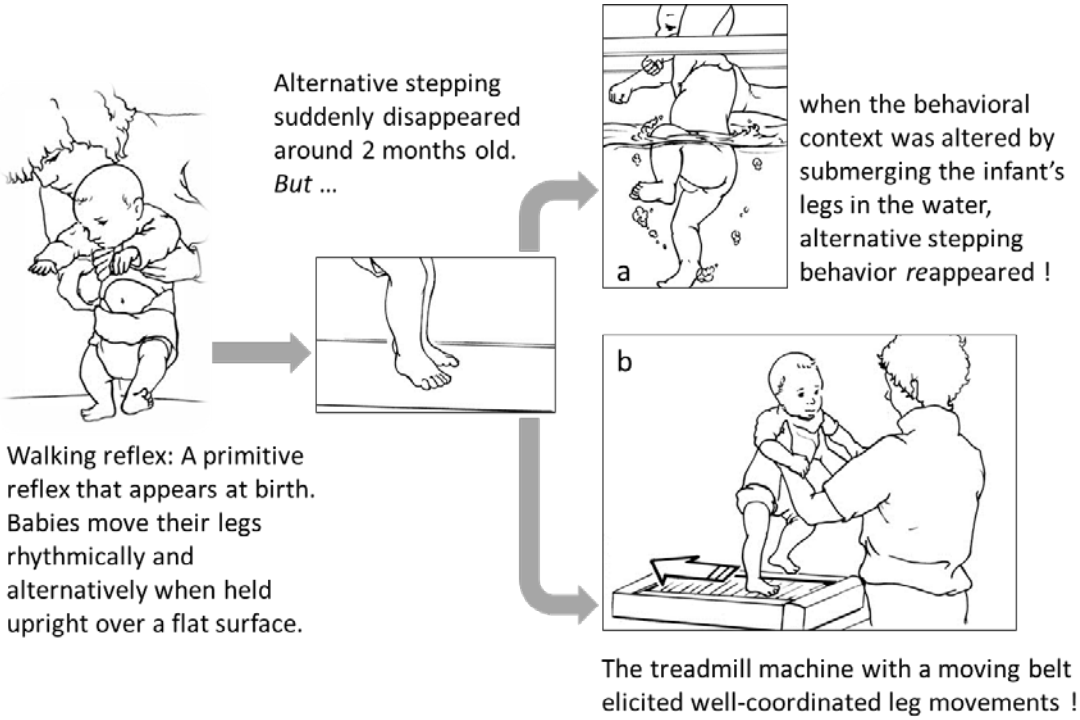



Figure 1. Disappearance of a newborn baby's stepping behavior and its reappearance in altered behavioral contexts (these illustrations were reproduced from Thelen & Smith, 1994).

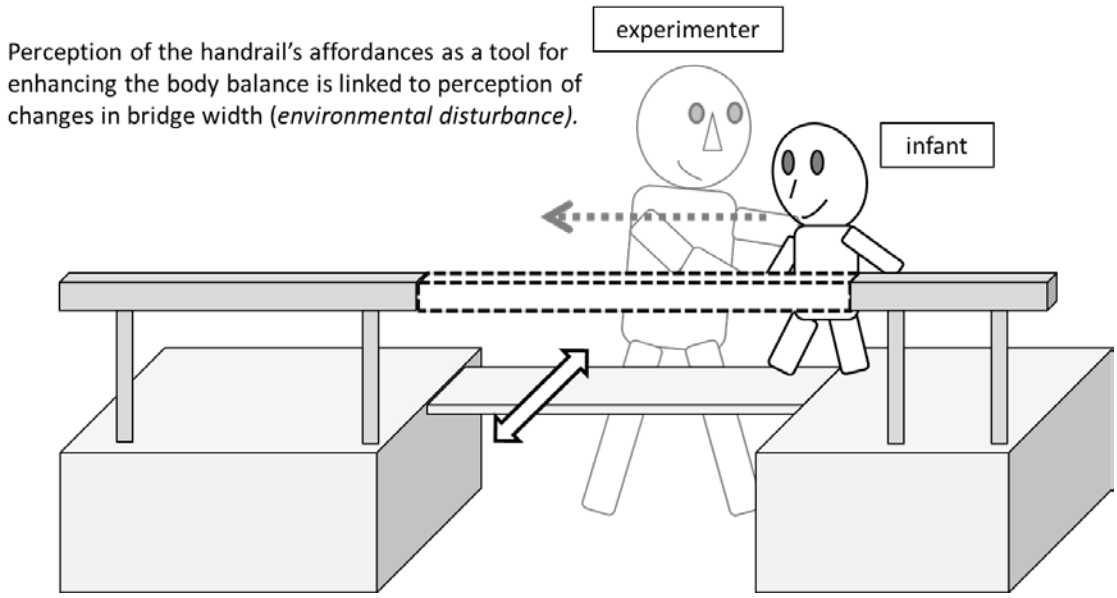



Figure 2. The impact of environmental disturbances on the behavioral decision-making and perception of affordances of the handrail as a tool that enhances the body balance (this illustration was reproduced from Berger & Adolph, 2003).

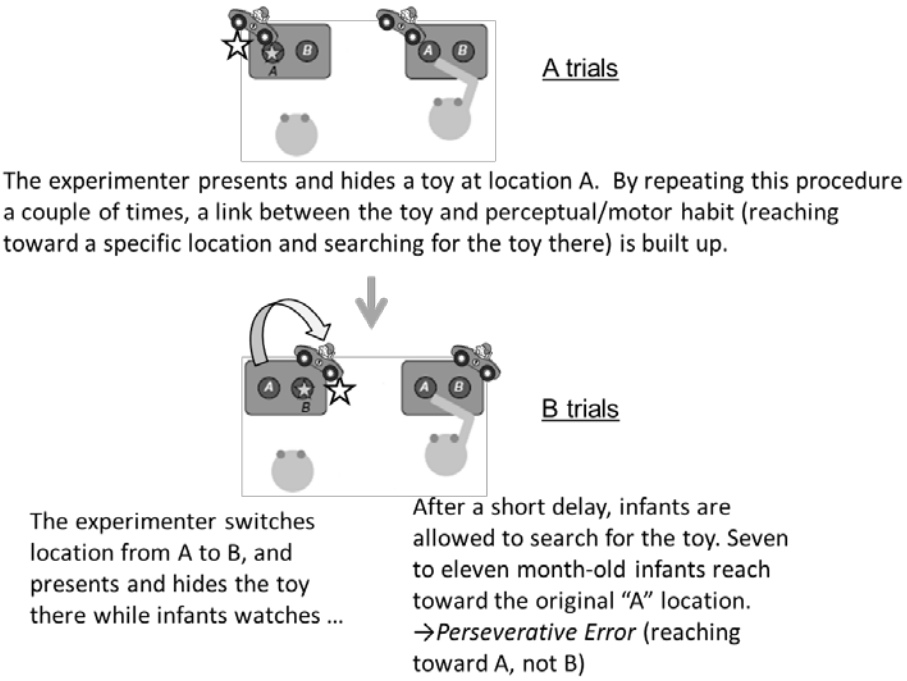
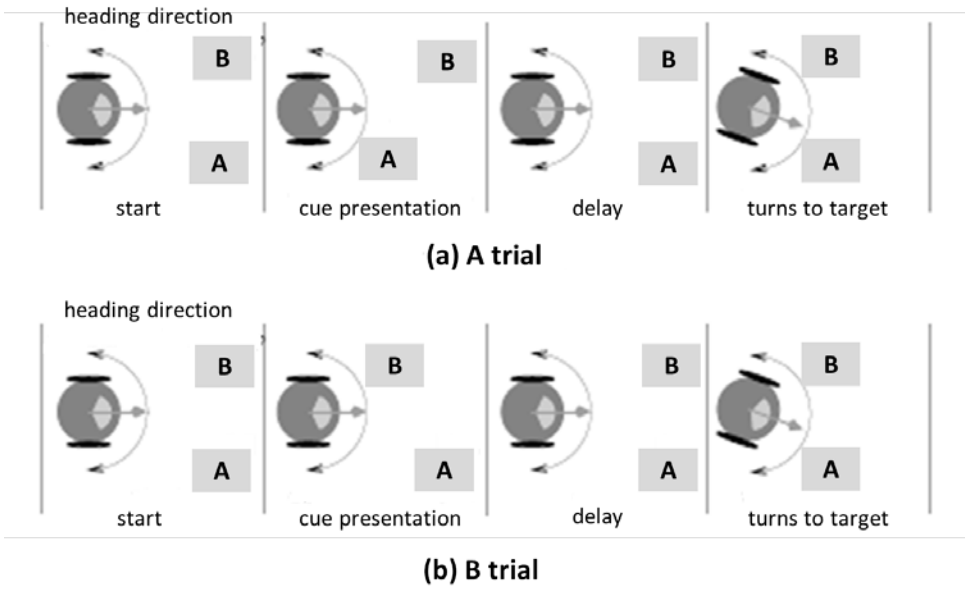



Figure 3. Schematic description of the canonical A-not-B error task




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 second delay the robot faces again the far flags (third column: delay). At the end of the delay both task flags are moved 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 4. Schematic description of the robotic replication of the A-not-B error task

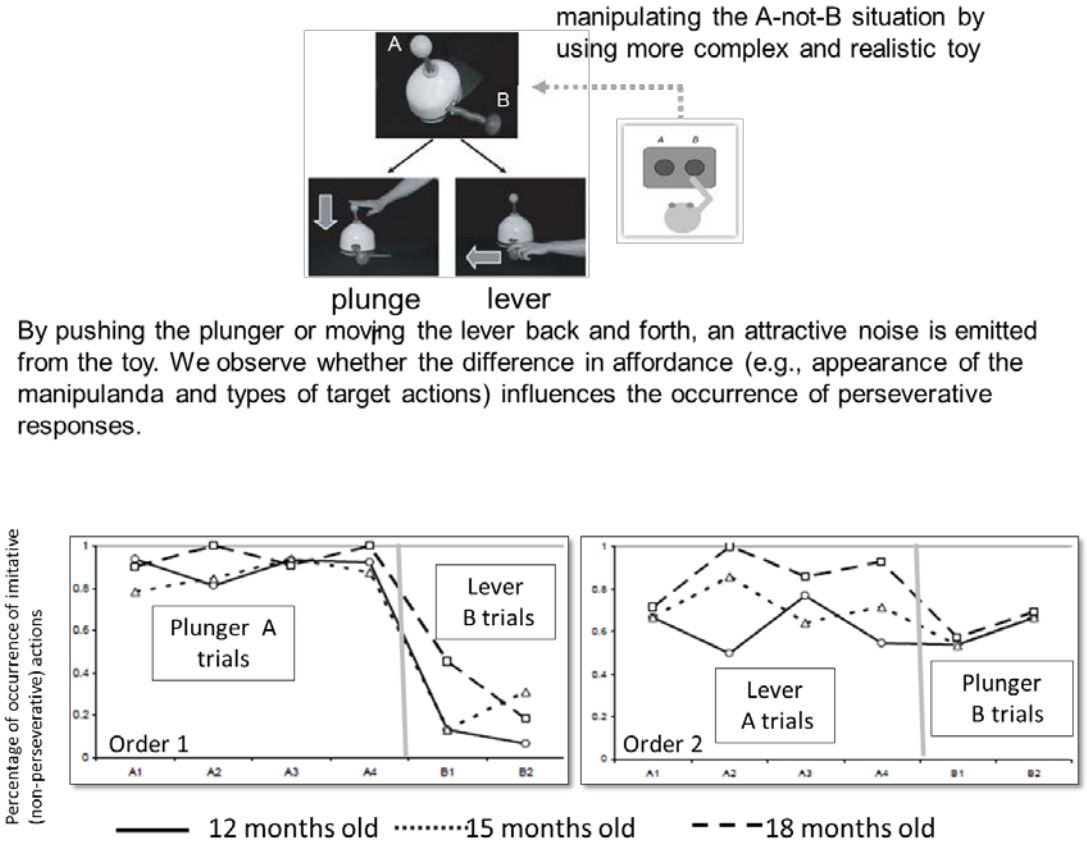



Figure 5. The choice task analogous to A-not-B using a complex toy and the occurrence of a perseverative response.