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Moving Toward a Grand Theory of Development: In Memory of Esther Thelen

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This paper is in memory of Esther Thelen, who passed away while President of the Society for Research in Child Development. A survey of Esther's career reveals a trajectory from early work on simple movements like stepping, to the study of goal-directed reaching, to work on the embodiment of cognition, and, ultimately, to a grand theory of development—dynamic systems theory. Four central concepts emerged during Esther's career: (1) a new emphasis on time; (2) the proposal that behavior is softly assembled from the interaction of multiple subsystems; (3) the embodiment of perception, action, and cognition; and (4) a new respect for individuality. Esther communicated these ideas to scientists and practitioners alike, so the ultimate benefactors of her work were children.

Child Development traditionally publishes the Presidential Address presented at the biennial meetings of the Society for Research in Child Development (SRCD). As President, Esther Thelen was slated to deliver the address in 2005, but her death on December 29, 2004 sadly precluded this event. In its place, a Memorial Symposium was held. One of Esther's trademark characteristics was to be inclusive, supportive, and collaborative—to bring people together. This is reflected in the large group of former postdocs, doctoral students, and research associates who collaborated to prepare that symposium, and then to prepare this archival paper for publication in *Child Development*. Esther was not only a mentor to us all, but also a dear friend. Thus, we appreciate the opportunity to share our collective vision of Esther and of her work with you.

Although being a supportive and generous friend was a core value Esther lived, our goal in this paper is to focus on her science. We use illustrations from her work to outline the themes emerging from her movement toward a grand theory of development. We end by proposing several future directions that are inspired by her work.

The First Steps: Setting the Stage

We begin by examining Esther's early work in infant and child development. This early phase is perhaps most vividly described as the kicking, stepping, and walking period. Many of the themes that characterize her work were foreshadowed in her earliest papers. These themes were also foreshadowed in the context of her early career: Esther followed her own unique path into the world of developmental theory.

Her earliest graduate research focused on the grooming behaviors of wasps. Esther was drawn to this, in part, by the ethologists' methods of observing animal behavior in its natural environment and discovering the underlying repeated patterns that "marked" their function and social impact. Esther

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This research was supported by NIH HD 22830 awarded to Esther Thelen. Many people contributed to making the 2005 SRCD Presidential Address such a memorable event. We are deeply grateful to the coauthors of the four talks: (Part 1) Donna Fisher-Thompson, Jody Jensen, Beatrix Vereijken; (Part 2) Dexter Gormley, J. Cole Galloway; (Part 3) Fred Diedrich, Linda B. Smith; (Part 4) Jana Iverson. We would also like to thank Dexter Gormley, Scott Robinson, and Vanessa Simmering for their invaluable technical assistance, and Brandi Dobbertin, Jeff Johnson, John Lipinski, Larissa Samuelson, and Wendy Troob for their many contributions both large and small. Finally, we would like to acknowledge Roger Bakeman, who hired Atlanta's Harmony Chorus for the event. We will never forget the moment when Esther finished speaking on video and the voices of children echoed through the room singing a South African freedom song. This gave everyone in the room a concrete example of the power of self-organization.

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discovered that actions that were repeated impacted subsequent behavior—even if the link between past and present behaviors was not transparent (Thelen & Farish, 1977). This pushed her to focus on process, on how and why these behaviors emerged and changed.

Rhythmical Stereotypies

Esther crossed over to the human side of animal studies with her dissertation. Here, she catalogued the spontaneous behaviors of babies in their natural settings—their homes—biweekly throughout the first year of life. Figure 1 illustrates the outcome of her painstaking efforts. She grouped the actions babies repeated into stereotypy categories, such as waving the arms, rocking in place, and kicking their legs. And she uncovered the developmental trajectory of each stereotypy, the timing of peak behaviors, and overlap among these different behaviors as well as their relation to the emergence of functional motor milestones. For example, kicking movements had their greatest frequency just before the onset of locomotion and rocking on hands and knees appeared just before crawling (see Figure 1). Her first publications based on this work appeared in animal behavior journals (Thelen, 1979, 1981a). But in 1981, she published a seminal paper in *Developmental Psychology* entitled ''Rhythmical behavior in infancy: An ethological perspective.''

She discovered that these simple, repetitive behaviors not only provide a window for researchers interested in studying motor control, but also provide infants with opportunities to become *active participants in their own learning*. This theme clearly resonated with researchers studying child development—it was quite remarkable that someone trained in biology drew such a strong and interested response with her first foray into the developmental literature. Perhaps developmental psychologists could already glean from her cogent arguments the seeds of a grand theory.

Shifting Patterns of Bilateral Coordination: Newborn Stepping

Of the many stereotypies infants generate, Esther was drawn particularly to kicking because it was repeated so frequently. Moreover, Esther's work revealed that the coordination patterns that underlie kicking were strikingly similar to the patterns that underlie newborn stepping. The puzzle was that newborn stepping disappeared within the first 3 months, whereas kicking continued and increased in frequency. What were the secrets to this mystery? Several researchers had proposed that maturing cortical centers inhibit the primitive stepping reflex or that stepping was phylogenetically programmed to disappear (Andre-Thomas & Autgaerden, 1966; Oppenheim, 1981; Peiper, 1963; Touwen, 1976).

To probe the mystery of the disappearing steps, Esther conducted another longitudinal study, confident that the answer would be revealed by focusing on the detailed development of individual infants and their individual differences. Thelen, Fisher, and Ridley-Johnson (1984) found a clue in the fact that chubby babies and those who gained weight fastest were the first to stop stepping. It appeared that for young infants to flex and extend their legs when upright (stepping; see Figure 2a) demanded more

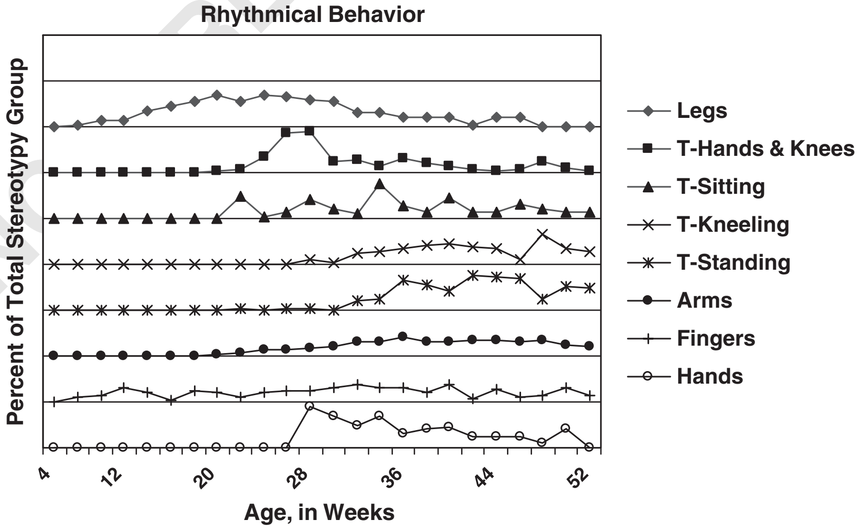
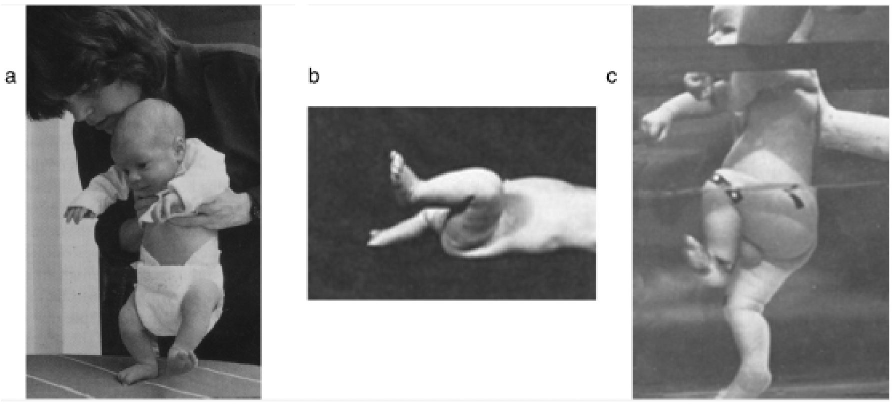


Figure 1. Frequencies of groups of rhythmical stereotypies during the first year (T = torso) (adapted from Thelen, 1981a).



Q9 *Figure 2.* Panel a shows newborn stepping. Panel b shows kicking. Panel c shows the reemergence of stepping when the infant is placed waist-deep in water.

strength than to flex one's leg when supine (kicking; see Figure 2b). To test this idea that strength was the key, Esther and her colleagues conducted two ingenious studies. In one, they placed small leg weights on 2-month-old babies, similar in amount to the weight they would gain in the ensuing month. They observed a significant drop in newborn stepping. In the other, they submerged older infants, whose stepping had begun to wane, in water up to chest levels (see Figure 2c). Step frequency immediately increased; more buoyant legs require less muscle force to lift.

These data demonstrated that traditional explanations of neural maturation and innate capacities were insufficient to explain the emergence of new patterns and the flexibility of behavior so evident in this case. Esther ultimately proposed that stepping—like any other behavioral pattern—is not something one *has*. Rather, *behavior emerges in the moment from the self-organization of multiple components*. This is elegantly illustrated in the stepping studies which show how the posture of the infant, the strength of an infant's muscles, and the pull from the environment all cohere in a moment in time to create or hinder leg movements. And, further, this example illustrates how changes in the components of this ''system'' over the longer time scale of development interact with this real-time, self-organizing view. Quite literally, Esther and her colleagues were able to *create development in the moment* by hindering the movements of young infants through the application of leg weights and recreating stepping in older infants by cleverly changing the environment.

A Dynamic Theory Emerges as Infants Take a Walk on a Treadmill

The case of the disappearing steps led Esther and her colleagues to move away from single cause views of development to consider the many, often nonobvious factors that influence developmental change. Critically, however, Esther's insights offered more than generalist statements that development was ''self-organizing'' and ''everything matters.'' This was brought to the foreground as she began to probe ties between infants' behaviors and those of other complex thermodynamic systems. For instance, she noted that both showed evidence of nonlinearity, both became increasingly less stable during periods of change, and both displayed a tendency to shift toward increased organization (Thelen, 1985; Thelen, Kelso, & Fogel, 1987).

These ideas emerged out of discussions with Scott Kelso, who, along with Peter Kugler and Michael Turvey, was beginning to use the principles of complex systems theories developed in physics, mathematics, and chemistry to explain adult human motor patterns and coordination (Kelso, Holt, Kugler, & Turvey, 1980; Kelso & Tuller, 1984). For most of us in the field of development, this approach became known as the dynamic systems approach.

Using a clever (some might say bizarre) context, she began to support babies upright on the belt of a motorized treadmill (see Figure 3a) to show that behavior self-organizes and that multicausality is at the core of developmental change. She designed a new longitudinal experiment, studying infants from 1 month of age, monthly, for 7–10 months. Embedded in the design were elements that allowed her to incorporate concepts central to the study of complex systems: (a) a *collective variable* captures the integrated behavior of the system under study (in the case of stepping, this was reflected in the phase relation between the legs during each step cycle; see Figure 3b for data on one phase relation—alternating steps); (b) *control parameters*—such as changes in

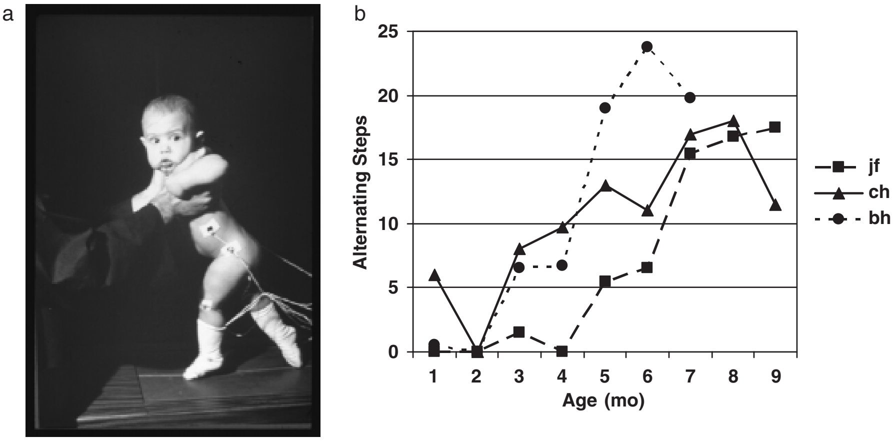


Figure 3. Panel a shows an infant walking on a treadmill. Markers on the legs and torso allow the computer to track the motion of the joints with a high degree of temporal and spatial precision. Panel B shows developmental changes in three infants' alternating stepping patterns (adapted from Thelen & Ulrich, 1991).

the strength of leg muscles—drive the system through periods of change; (c) behavioral change is *nonlinear*—early in the first year, infants produced few steps on the treadmill, but there was a distinct increase in stepping, typically by 3 months of age, that occurred at different times for different infants (see Figure 3b); (d) behavior is *self-organized*—the motion of the treadmill helped assemble all the components involved in stepping such that infants showed stepping patterns when placed on the belt even when they failed to show stepping in other contexts. The results of this study were published as a monograph for the SRCD (Thelen & Ulrich, 1991). This monograph served as a tutorial that explained dynamic systems constructs, and it provided a template for how to apply these constructs to the study of behavioral development.

A key finding from this monograph is that the same context elicited different behavior patterns over time and, further, that multiple factors affected the patterns that emerged. Early stepping consisted of multiple unstable patterns, including alternating, but also single, parallel, and double steps. As infants acquired more muscle strength, an improved ability to control segments of the body, more experience in the upright posture, and so on, stepping reorganized. Critically, although some form of stepping pattern could be elicited over much of the first year of postnatal life, walking only emerged after months of exploration. Esther and Bev Ulrich concluded that stepping and, ultimately, walking are not innate or prescribed. Rather, they are self-organized and emergent, reflecting the assembly of multiple subsystems within the infant's history of activity in context (Thelen & Ulrich, 1991).

Guiding Us Through the Next Steps

One of the underlying goals of basic science is to understand how systems work sufficiently well to intervene, when necessary, and provide novel solutions to help people overcome behavioral problems. Esther's early experiments utilized tasks that emphasized kicking, stepping, and walking, behaviors of particular interest to therapists working with early motor disabilities. Researchers working on motor problems continue to build on her work to study neuromotor responses of infants born prematurely, as well as infants born with intraventricular hemorrhages, Down syndrome, cerebral palsy, and spina bifida (Angulo-Barroso, Ulrich, & Tiernan, 2004; Heriza, 1988; Ulrich & Moerchen, 2005; Ulrich, Ulrich, Angulo-Barroso, & Yun, 2001). These translational efforts have proved quite promising, in part, because the contexts Esther created readily elicit motor activity. By carefully controlling and manipulating the subsystems involved in, for instance, stepping behaviors, one can push the system into new forms of organization and uncover control parameters—intrinsic or extrinsic—that give us leverage to elicit behavioral change. Ultimately, these may be used to help children assemble new, more stable and more functional behavioral patterns.

Esther published nearly 30 empirical papers in which kicking and stepping were the primary focus. But these specific behaviors were merely tools for her focus on larger theoretical issues of learning and development. By her painstaking efforts, she incorporated profound empirical discoveries into her evolving theory. Her goal was to establish a grand theory of development with general principles that apply across varied phenomena and traditionally disparate domains. And in so doing, she wanted to reach out and reach in, so that the ultimate benefactors of our work are children. Lofty goals, to be sure, but what a wonderful roadmap she left us.

Learning to Reach: Mapping Intentions With Intrinsic Dynamics

Kicking and stepping are repetitive movements that are not always performed with an obvious goal in mind. What happens when infants' movements become clearly goal-oriented? Can the principles of dynamic systems theory (DST) be applied to the development of goal-oriented behaviors? Do patterns of, for instance, reaching movements self-organize as with kicking and stepping? What do infants need to learn to obtain a desired toy? During the 1990s, Esther turned to these questions as she sought to generalize her ideas about the nature of development.

From a Classical to a Systems View of Infant Reaching

Before Esther's work, the development of infant reaching was thought to occur in two phases that all infants traversed in a similar fashion (see Bushnell, 1985, for review). In a first developmental phase beginning at about 3 or 4 months of age, infants' reaches were characterized by very discontinuous, zigzagging trajectories. In a second phase appearing around 8 months of age, infants began to reach for toys following a more direct path. The classic account of these two developmental phases focused almost entirely on visual control of reaching. During the first phase—called the visually guided reaching phase—it was assumed that infants' discontinuous trajectories reflected their continuous effort to monitor and visually control the hand trajectory. In the second phase—called the visually elicited reaching phase—infants could look at the target, anticipate an appropriate hand trajectory, and move their hand to the target using a fairly straight path without visual monitoring.

Esther's work on infant reaching challenged this view of development in two key ways. First, Esther objected to the heavy emphasis on visual control in earlier accounts. By her view, the development of reaching did not reflect changes in a single factor; rather, she saw infant reaching as emergent from the assembly of many components. To reach out and grab an object, infants need to be motivated. They need to be able to localize the object in three-dimensional (3-D) space. They need to understand whether the object is reachable, and they need to transduce the perceived 3-D space into their body space. They need to be able to plan ahead and anticipate how the trajectory will unfold. They need to be able to correct their movements online as their hand approaches the toy. They need to be able to lift and stabilize the arm as they reach while maintaining the stability of the head and the trunk. And, they need to remember what works in context and distinguish this from what does not work. Although vision is certainly involved in some of these challenges, vision alone cannot account for how infants learn to reach given these many interacting factors. The challenge, then, is to understand how infants manage to assemble all these factors to perform a successful reach.

The second point that Esther challenged was the universality of the two-phase account of infant reaching. She thought the emphasis needed to be on the individual—on the unique motor problems each infant must overcome due to each infant's unique movement characteristics. In particular, infants need to discover their own, individual, intrinsic movement characteristics to develop proper control of the arm and improve movement coordination over time.

Individual Development Matters: A Tale of Two Infants Learning to Reach

This idea is beautifully illustrated in the story of Hannah and Gabriel learning to reach. Gabriel and Hannah were two of the four infants that Esther and her colleagues followed every week over the first year of life, from 3 to 52 weeks (e.g., see Thelen et al., 1993; Thelen, Corbetta, & Spencer, 1996). Gabriel began reaching when he was 15 weeks old. Hannah performed her first reach attempts when she was 20 weeks old. Each child displayed very different behavioral characteristics on the weeks before and at reach onset. Gabriel was a very active, energetic infant who was flapping both arms up and down along the sides of his body. He was often flapping regardless of whether the toy was visible or not. At reach onset, these flapping patterns became an integral part of his goal-oriented movements. Typically, when the toy was approaching his reaching space from the side to the midline, Gabriel flapped and reached for the toy by throwing his arm up and forward. This resulted in swiping at the toy and, occasionally, a toy contact!

Hannah had a completely different style. She was a much more quiet, lower energy child. At reach onset, her strategy was to stare at the toy intensely before moving her arm forward and making contact with the toy. Because she was quiet before reaching and moved her arm forward slowly, her reaches seemed much more controlled and mature than Gabriel's, but that was only temporary. Indeed, a few weeks after her first reaches, Hannah became more active and she began to show the torturous reaching trajectories characteristic of Gabriel's early reaches.

By observing Hannah and Gabriel week by week (along with two other infants), Esther and her colleagues discovered that the early discontinuities in reaching trajectories did not result from visual guidance of the hand; rather, they emerged as the product of high movement speed and associated large passive and active forces combined with a lack of control. This is evident in the kinematic profiles of Gabriel's and Hannah's first reaches. Figure 4a shows the displacement of Gabriel's hand during an 8-s segment of motion. This segment shows a continuous movement performed before (solid line), during (dashed line), and after (solid line) the reach. Figure 4b shows the corresponding velocity profile for this segment of movement, with the onset and offset of the reaching segment marked by the two vertical bars. Gabriel was initially producing fast movements—flaps—with several high peaks of velocity before the toy came into view. Then, when the toy appeared, Gabriel turned a flap into a reaching movement, again generating a series of high velocity peaks. This reaching movement (dashed lines in Figure 4a) was embedded within the ongoing stream of activity (solid lines), and the hand path that resulted was very discontinuous.

When we contrast these data with Hannah's first reach (see Figure 4c and d), a very different picture emerges. Hannah's movement trajectory (see Figure 4c) was much simpler and more direct than Gabriel's trajectory. Why is this the case? Hannah's movement velocity (see Figure 4d) was almost three times lower than Gabriel's velocity on his first reaching attempt. Thus, while Gabriel was generating high motion-dependent forces that pushed his arm off the intended trajectory leading to many corrections, Hannah generated much smaller forces and was able to produce a fairly straight trajectory on her first reach.

But Hannah's seemingly good reaching skill was only temporary. During the weeks after these infants began reaching, Gabriel and Hannah modulated their reaches in unique ways to overcome the challenges set up by their individual movement tendencies. Specifically, within the few weeks after reach onset, infants had to learn to either ramp up or clamp down on these movement tendencies to more effectively bring their hands to the toy. Gabriel, who was generating high and fast velocity peaks, had to learn to slow down his movements. Within 3 weeks, he showed a dramatic decline in the number of velocity peaks in his reaches with an associated increase in path straightness. By contrast, Hannah, who produced much slower movements, had to learn to

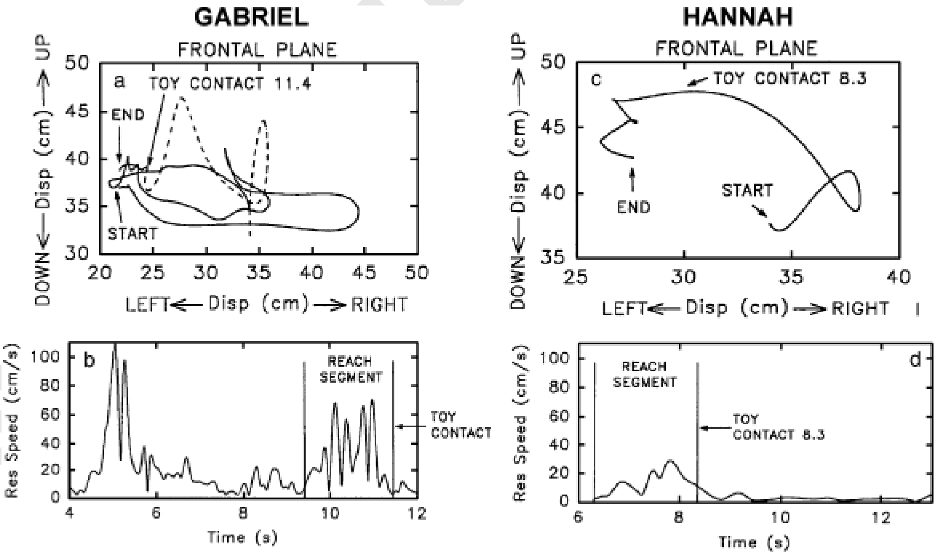


Figure 4. Kinematic profiles of Gabriel's and Hannah's first reaches during an 8-s segment. (a) Endpoint trajectory of Gabriel's right arm movement before (solid line), during (dashed line), and after (solid line) reaching for a toy at midline. Gabriel's reaches were embedded in a continuous movement stream. (b) Corresponding resultant speed profile with demarcation of the reaching segment for Gabriel. (c) Endpoint trajectory of Hannah's right arm movement when reaching for a toy at midline. (d) Corresponding resultant speed profile with demarcation of the reaching segment for Hannah.

inject more energy into her reaches to lift her arm against gravity and extend her hand up and forward to the toy. She became more active in the weeks following reach onset, with an increase in movement velocity and a decrease in path straightness. Thus, Hannah, who looked pretty skilled on her first reaching attempts, became much worse in the few weeks following reach onset (Thelen et al., 1993).

Developmental Change Occurs Through Exploration and Selection

In addition to showing that infants follow their own unique trajectories, this study of infant reaching revealed that exploration and selection is a key agent of developmental change. To improve over time, each infant experienced and explored a wide range of movements, ultimately leading to the discovery and selection of an optimal way to assemble the many components involved in a reach. Such exploration and selection is evident when we consider the full set of changes in Gabriel's and Hannah's reaching characteristics from reaching onset to the end of their first year of life. Figure 5 shows changes in several kinematic variables across the first year for reaching (Figure 5a–f and i–n) and nonreaching movements (Figure 5g, h, o, and p) for Gabriel and Hannah, respectively (Thelen et al., 1996).

We want to highlight three points about these data. First, goal-oriented reaches were always embedded within a movement context that showed very similar kinematic characteristics. For instance, changes in the velocity of infants' reaches over the first year (Figure 5a–c and i–k) paralleled changes in the velocity of infants' nonreaching movements (Figures 5g, h, and p). Thus, when infants were more active as reflected in periods of higher average speeds in nonreaching movements, reaches were also performed with higher movement speeds (see the dashed arrow line marking the active period for Gabriel and Hannah). Likewise, when infants were less active as reflected in periods of lower average speeds, their reaches were also slower.

Second, these graphs illustrate the concepts of exploration and selection. Exploration is reflected in an early phase from reach onset to about 30–36 weeks, where all the speed and trajectory parameters fluctuate up and down and show unstable and changing curves (see ''exploration phase'' in Figure 5). In this phase, infants explored a wide range of movement parameters and movement solutions. They tried fast and slow movements, learning the effect of these varied speeds on their ability to acquire the toy (see Thelen et al., 1996). This exploration generated crucial sensory-motor experience needed to learn to calibrate movements and feel the boundaries of control within the reaching task. This resulted in selection during a second phase from 30 to 36 weeks through the end of the first year (see ''selection phase'' in Figure 5). In this phase, movement parameters settled near particular values and showed much more stability over time as infants discovered, for instance, an optimal reaching speed that led to more stable and efficient reaches (Thelen & Corbetta, 1994; Thelen et al., 1996).

The third critical point illustrated in Figure 5 is that Gabriel and Hannah (as well as the other two infants in this study) converged on similar movement characteristics at the end of the first year despite their very different starting points at reach onset. For instance, they converged to a similar number of movement units, comparable movement straightness, and similar movement speed when contacting the toy (see the small side arrows in Figure 5). This reveals that different developmental pathways can lead to similar outcomes (Thelen et al., 1996).

New Lessons About Learning to Reach

In conclusion, Esther taught us a number of wonderful lessons about the development of infant reaching. She taught us that developmental change happens at the level of the individual—all infants do not develop motor skills following the same mold. Instead, each infant experiences unique and different movement challenges that call for different solutions and contribute to the formation of a distinct developmental pathway. In this way, she moved us away from earlier views about the visual guidance of the hand and universal phases of development. Rather, Esther's work demonstrated that reaches are carved out from the intrinsic dynamics of infants' self-generated arm movements as they explore a range of movement possibilities and select viable solutions to meet the demands of the task. In this achievement, body and mind come together as infants assemble the many components that make a reach: the biomechanics of the body, the details of the specific environment including the perceived location of the toy, the speed and force needed to extend the arms away from the body, the ongoing movement and postural context, and so on. This integration of body and mind is a fundamental characteristic of all goal-directed actions and creates a bridge to an embodied view of cognition and behavior (for an additional discussion of these lessons, see Corbetta & Thelen, 1994, 1996, 1999, 2002; Spencer & Thelen, 2000; Spencer, Vereijken, Diedrich, & Thelen, 2000).

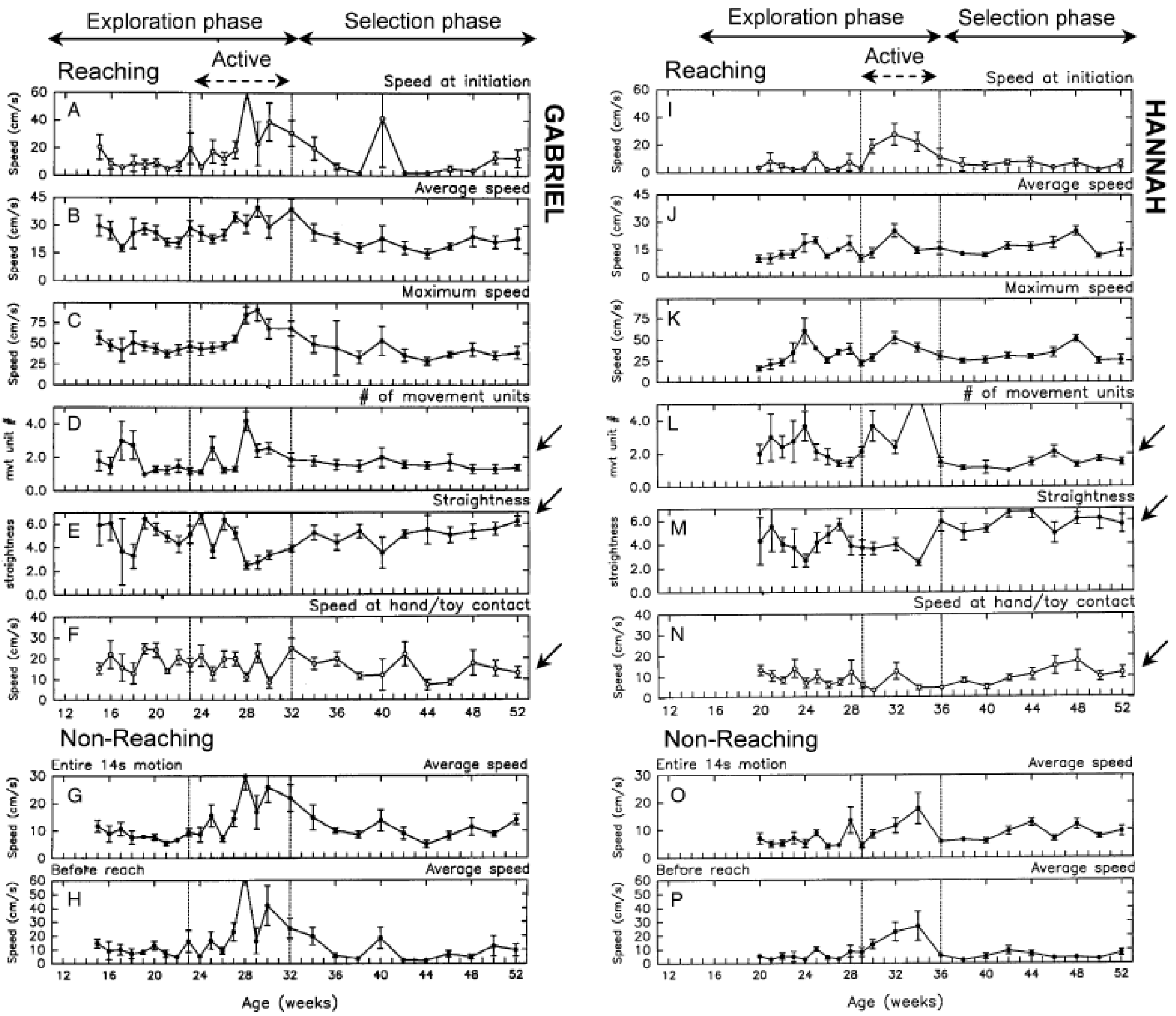


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Figure 5. Kinematic variables of Gabriel's and Hannah's reaching and nonreaching movements from the onset of reaching to the end of the first year. Panels a – f: means and standard errors of movement speed at reach initiation, average reaching speed, maximum reach speed, straightness of the path, number of movement units, and speed at hand – toy contact for Gabriel. Panels g and h: means and standard errors of the average speed of all nonreaching movements and the segment of motion before reach initiation for Gabriel. Panels i – n: means and standard errors of movement speed at reach initiation, average reaching speed, maximum reach speed, straightness of the path, number of movement units, and speed at hand – toy contact for Hannah. Panels o and p: means and standard errors of the average speed of all nonreaching movements and the segment of motion before reach initiation for Hannah. Arrows at the top indicate phases in the development of reaching skill. Arrows to the right indicate common values of kinematic variables for both infants at the end of the first year.

From Action to Embodied Cognition: Bridging the Great Divide

By this point, Esther had learned that infant motor behaviors—both rhythmic movements with the legs and goal-directed reaches—emerge as the product and confluence of multiple factors. She had discovered that learning new movement patterns was not the same for all infants; individual infants must explore a wide range of behaviors to discover and select their own unique solutions in the context of their intrinsic dynamics and movement history. Finally, progress in motor development requires the integration of body and mind as infants bring together their physical characteristics with the environmental and movement context to find optimal and flexible behavioral solutions. These were key insights in motor development, but did these insights extend beyond the realm of stepping, kicking, and reaching?

To address this question, Esther started to think deeply about the connections between her work in motor development and work in other domains of development. She turned naturally to cognition. Many of the dominant questions in cognitive development stem from Piaget, who asked how children move from the sensorimotor origins of thought to abstract cognition. Contemporary theorists have built on this idea, emphasizing the transformation from perceptual to conceptual processing (e.g., Mandler, 1988) or the construction of more sophisticated forms of cognition built upon innate ''core'' knowledge modules (e.g., Spelke, 1998). Critically, such approaches have postulated a divide between the ''cognitive'' and the ''sensorimotor,'' either through the pursuit of abstract forms of cognition without an understanding of their sensorimotor origins or by creating a distinction between the cognitive and the sensorimotor from the beginning.

This divide was evident when Esther contrasted the fields of motor development and infant cognition. In motor development, researchers try to understand the processes that result in a kick or a reach or a look—these behaviors are interesting in their own right and reveal characteristics of how perception, action, and cognition all come together to assemble a behavior in context. In infant cognition, by contrast, a reach or a look is just a way for infants to demonstrate knowledge, that is a way to get at what infants *know*. Given this, contemporary theories of infant cognition have little to say about the role of the body in mind.

Esther questioned the divide between ''pure'' sensorimotor behavior and cognition. Indeed, in collaboration with Linda Smith, she denied the very existence of this divide. She argued that mental activity is embodied—thought is always grounded in perception and action (e.g., Thelen, 2000; Thelen & Smith, 1994). This followed Piaget's tradition in invoking the importance of the sensorimotor origins of thought. But rather than viewing development as movement toward the abstract and away from perception–action, Esther believed that—for infants and adults alike—cognition and action are not separate. Instead, cognition is inextricably linked to perception and movement. There is no cognition in the absence of perception and action.

Embodied Cognition and the Piagetian A-not-B Task

Esther began exploring this connection between cognition and action through several traditional developmental tasks. Her detailed analysis of the dynamics of reaching first led her to a classic Piagetian task: the A-not-B task. In this task, infants watch while a toy is repeatedly hidden in one location. After a brief delay, infants reach to that location and uncover the toy. After several trials to this ''A'' location, infants watch while the toy is hidden in a second ''B'' location a few inches away. Almost without fail, 8- to 10-month-old infants will reach back to the original A location after a short delay, that is, they reach to A and not B (Piaget, 1954; Smith, Thelen, Titzer, & McLin, 1999). According to Piaget (1954), this ''A-not-B error'' was indicative of infants' incomplete ''object concept.'' More contemporary theories have emphasized that problems with spatial coding, search strategies, or fragile object representations underlie this error (see Marcovitch & Zelazo, 1999; Munakata, 1998; Wellman, Cross, & Bartsch, 1987).

Instead of thinking about what this task tells us about what infants *know*, Esther and her colleagues began their analysis of the A-not-B error by focusing on what infants *do*. And what they do in this task is look and reach again and again to a poorly specified target at an A location, only to look and reach again to this location after looking at an event at B. Thus, Esther asked whether the processes that underlie repeatedly looking at and reaching to a location could explain the complex pattern of behavior revealed by decades of research on this odd error in infancy.

This question led Esther and her colleagues to develop the dynamic field theory (DFT) of infant perseverative reaching (Thelen, Schöner, Scheier, & Smith, 2001). This theory captures the processes that underlie infants' decisions to act based on the integration of the immediate environmental stimuli as well as the short-term and long-term history of reaching in the same and similar situations. The theory is captured schematically in Figure 6. The theory starts with the concept of an activation field that captures how infants plan and remember actions. The activation field depicted in Figure 6 shows two ''peaks'' of activation distributed across a movement parameter, reaching direction. There is a large peak of activation over the A location and a smaller peak over the B location. This represents a stable ''decision'' to move to A: infants have a strong, supra-threshold representation of A that can subserve a reaching movement to this location.

What factors contributed to this activation peak at A? Figure 6 illustrates three inputs that have been shown to influence infants' reaching decisions in the A-not-B situation. The first input is the task input. This captures the pattern of activation generated by

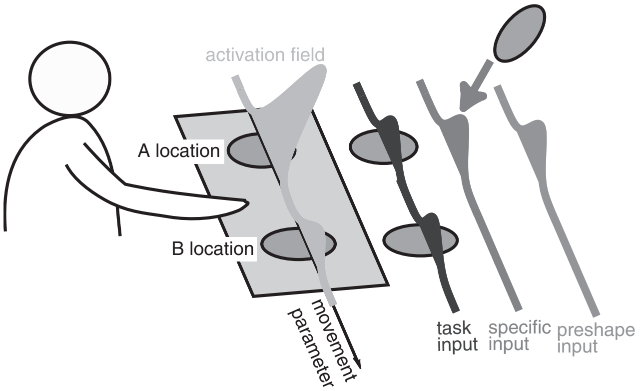

Figure 6. Schematic of the A-not-B task. The infant (far left) sits in front of two targets (A and B locations). The activation field (in green) captures the infant's decision to reach as a pattern of activation distributed across the behavioral dimension (the direction of the reach). When activation reaches threshold at one of the locations, the infant decides to reach to that location. Three inputs contribute to the activation level. The task input (shown in blue) represents the perceptual layout of the space, including the two reaching targets. The specific input (shown in pink) is the transient event that draws attention to one location (i.e., the experimenter hides the toy at A). The preshape input (shown in gray) represents the infant's perceptual-motor memory of previous reaches to A. In this example, the task input is equal for both the A and B locations, but there is a peak at A from the specific input (the experimenter cued the A location) and from the preshape (the infant had previously reached to A). This results in a suprathreshold peak at A (shown in green), which results in a reach to A.

the perceptual layout of the task space, for instance, the two covers in Figure 6. It is through this level of input that task variations like distinctive targets or multiple locations have an impact (e.g., Bjork & Cummings, 1984; Bremner, 1978; Butterworth, Jarrett, & Hicks, 1982; Diedrich, Highlands, Thelen, & Smith, 2001). The second input—the specific input—captures the pattern of activation produced by the attention-grabbing cue of waving the toy or the lid (or whatever the experimenter does to draw the infant's attention to one location; see Clearfield, Dineva, Smith, Diedrich, & Thelen, 2006; Smith et al., 1999). The final input—the preshape input—captures the pattern of activation produced by the just-previous past. In particular, this input reflects infants' perceptual-motor memory of past reaches to the A or B locations. In Figure 6, this input has some activation centered over the A location, reflecting an infant's past reaches to A on a series of A trials.

How does the activation field—in concert with the three inputs depicted in Figure 6—shed light on the processes that underlie the A-not-B error? On the first A trial, infants face two identical reaching targets (the side-by-side covers or lids); thus, the task input is symmetric—it does not specify either location. As infants watch, the experimenter cues them to reach to the A location, by either hiding a toy or waving the lid. This produces a specific input centered at A. When the box is moved within reach after a short delay, the specific input to A is strong enough and the memory for that cue sufficiently long lasting that they reach in this direction. This reach also creates a perceptual-motor memory which lingers after the reach and can "preshape" the activation field on subsequent trials. Thus, on the second trial to the A location, infants are already slightly biased by their previous decision to reach in the same direction. With more and more reaches to A, the perceptual-motor memory builds up such that, by the first cue to B, there is a relatively strong tendency to reach to A (i.e., a strong preshape input). This tendency, combined with the symmetric task input and a long delay on the B trial, sets infants up to perseverate. In particular, infants perseverate because the specific input at B fades during the delay and is overtaken by the lingering memory of past reaches to A.

Bringing Together Theory and Experiment

Through a combination of simulations and new experimental evidence, Esther and her colleagues showed that the decision to reach to A or B in the A-not-B task could be entirely determined by infants' short-term and long-term history in the task, their action planning abilities, and the inputs in the experimental context (e.g., Clearfield, Smith, Diedrich, & Thelen, 2006; Diedrich, Thelen, Smith, & Corbetta, 2000; Diedrich et al., 2001). For instance, by thinking about the dynamics of reaching and looking, these researchers demonstrated that *hidden toys were unnecessary to produce the error* (Smith et al., 1999). Similarly, visual distractions had a profound influence on infants' pattern of reaching—a simple tap on the table near A or B could create stronger perseveration or create a tendency to reach correctly to B (Smith et al., 1999). They also showed that the probability of perseverating on the B trials is a function of the number of reaches to A on the A trials: the more reaches to A, the stronger the ''pull'' to A on the B trials; the more spontaneous reaches to B on the A trials, the weaker the pull to A on the B trials (Diedrich et al., 2001; Smith et al., 1999; see also Marcovitch & Zelazo, 1999).

In several additional studies, Esther and her colleagues demonstrated that infants' decision to reach to A or B was truly embodied—there was an obligatory coupling between body and mind. For instance, perseveration is tightly linked to infants' developing reaching abilities (Clearfield & Thelen, 2001; Clearfield, Smith, et al., 2006; Diedrich et al., 2001). Initially, when infants are very unskilled, they reach correctly in the A-not-B task. According to the DFT, this occurs because infants' perceptual-motor traces get ''smeared out'' as they reach for the A location in different ways from trial to trial (Clearfield, Smith, et al., 2006). Thus, there is less of a bias to A on the B trial due to a less focused preshape input (see Figure 6). As another example, Esther and her colleagues showed that changes in the feel of the body between the A and B trials can disrupt perseveration (Clearfield, Diedrich, Smith, & Thelen, 2006). When infants' arms were weighted during the A trials and the weights were removed in between the A and B trials, infants reached correctly to B on the subsequent B trials! Infants also reached correctly on the B trials when weights were added in between the A and B trials. By contrast, when infants wore weights through an entire session, they perseverated at the usual rate. Thus, disrupting the feel of the arms between the A and B trials was enough to disrupt perseveration; as long as the arms felt the same throughout, infants perseverated at the normal rate.

In her Presidential Address to the International Society on Infant Studies in 1998, Esther outlined the importance of these findings: what infants know is always assembled, in the moment, with contributions from memory, attention, and action (Thelen, 2000). Cognition is embodied. Infants' decision to reach is based on much more than whether or not they have an object concept. Instead, the decision to reach is based on what the infants have just done, their reaching skill, the feel of the body, the salience of the cue, and the perceptual layout of the task. Thus, this reaching task that was assumed to provide a direct window into infants' abstract concepts is actually a window into the complex interactions among perception, action, and cognition in infancy.

Embodied Cognition and the Dynamics of Infant Habituation

Armed with this new understanding of embodiment in infancy, Esther moved on to examine another task thought to provide a window into infants' minds—infant habituation. Infant habituation tasks comprise the backbone of the field of infant cognition. Infants are shown a display or an event over and over until looking time decreases. Then, they are shown a slightly different ''test'' display or event. If looking time increases, researchers state with certainty that infants discriminated between the two events and, perhaps, that this reflects infants' knowledge or understanding of some concept. As with the A-not-B paradigm, this leap from what infants *do* to what infants *know* troubled Esther. She began to think about what infants do in this task: they attend to the display, they visually process it, and they look and look away from the display. Her focus was on the multiple causes that produce these behaviors, and how the history of the system might influence whether or not infants look at the display at test.

To understand the complex looking dynamics at work in infant habituation, Esther and Gregor Schöner applied the concepts of the DFT to a classic habituation task (Schöner & Thelen, 2006). In particular, they focused on how the trial-to-trial history of perceiving, attending, and acting in context influences the ''decisions'' infants make to look or not look at stimuli in habituation tasks. Using a series of simulations, they showed how multiple factors influence infants' decisions to look at a stimulus: the history of looks across trials, the salience of the displays, the number and order of habituation and test trials, and the complexity of the displays. They concluded that—as with the A-not-B paradigm—habituation tasks are not a window into infants' minds, divorced from attention, perception, and action. Rather, infants' decisions to look or not to look are a result of the complex interactions among these diverse and fully embodied processes.

From Knowing to Acting in the World

The importance of Esther's work on infant cognition is not just in the particular tasks or findings that she and her colleagues eloquently explained. Rather, what we take away from this work is that cognition is embodied—and this has concrete conceptual and methodological consequences. This view of cognition shifts the focus away from what babies *know* in the abstract to a shared emphasis on the perceptual and movement dynamics that produce behavior. The traditional view that reaching or looking gives us direct access to the contents of mind is no longer tenable. As long as our entry into infant cognition is through reaching or looking, the dynamics of these behaviors must be considered, that is, the developmental history and real-time dynamics of the response cannot be separated from the constructs the response is designed to measure. Perception and action are not bystanders in cognition. Rather, cognition always reflects the dynamic interplay of mental and bodily processes embedded within a rich context.

Reaching Out: Dynamic Systems in the World

Movement played a central role in Esther's career, not simply in the topics she studied, but movement in her own thinking as well. Two trajectories emerge from a survey of her career. The first is movement from studying simple responses to increasingly complex phenomena, including cognition. In Esther's early career, she discovered how infants assemble simple movements like stepping and walking on a treadmill from multiple components including the spring-like character of leg muscles. Later, when studying goal-directed actions like reaching, she discovered that the characteristics of infants' bodies as well as their energy levels had a profound influence on the emergence of goal-directed actions and in generating the torturous paths so typical of early reaching. But through a process of exploration and selection, infants harnessed these intrinsic dynamics as body and mind came together to make straighter, more efficient reaches. These early hints at the embodiment of cognition were brought to the foreground as Esther moved into the domain of infant cognition. Here, she and her colleagues specified the neural dynamics at work as infants made decisions about where to reach in the A-not-B task or where to look in a habituation task.

Importantly, as Esther moved from simple responses to increasingly complex phenomena, she did not partition the child up as the focus expanded. Rather, she viewed the child-in-context as a complex system of reciprocally coupled and reciprocally interactive components. Moreover, she showed an impressive ability to integrate seemingly disparate phenomena: from leg muscles and rhythmic movements to arm muscles and goal-directed actions; from reaching movements and movement speed to the A-not-B task and the role of motor skill in this classic cognitive task; from reaching and looking at lids and toys to looking at complex stimuli in infant habituation.

These commonalties led Esther to emphasize the role of *general processes* in shaping development. This view ran counter to other modern proposals about the state of developmental theory, which claim that ''Piaget was wrong: broad, general explanations seem 'increasingly implausible' (Gopnik, 1996, p. 221) and efforts are better spent working out the details, domain-by-domain. The traditional big issues of developmental theory . . . should be cast aside in favor of specific theories about content'' (Thelen & Bates, 2003, p. 378). In contrast to this view, Esther and Elizabeth Bates wrote, ''we state forthrightly that we do believe that there are general principals of development: mechanisms and processes that hold true whatever the content domain'' (Thelen & Bates, 2003, p. 378).

Esther's pursuit of these general developmental processes highlights the second trajectory in her career—movement from metaphor to formal theory. Her career began with an ethological and ecological perspective that included intensive observations of children in a number of detailed longitudinal studies of kicking and reaching (e.g., Thelen, 1981b; Thelen et al., 1993). This large body of empirical work led initially to a systems view and a rejection of nativism as a viable approach to understanding development. Later, in a seminal paper coauthored with Beverly Ulrich, Esther introduced concepts of DST to developmental researchers—collective variables, control parameters, nonlinearity, self-organization, attractors, stability, and multicausality—laying out a recipe on how to study developmental process (Thelen & Ulrich, 1991). These ideas were expanded in her 1994 book with Linda Smith (Thelen & Smith, 1994). This book postulated that systems thinking was not solely applicable to motor development and motor control; rather, the concepts of DST could be applied across all domains of development including cognition (for elegant demonstrations of this, see Fischer & Bidell, 1998; Lewis, 2000; van der Maas et al., in press; Van Geert, 1998). Esther, Linda Smith, and their colleagues demonstrated this forcefully in a series of elegant and counterintuitive experiments on the Piagetian A-not-B error (Smith et al., 1999).

Next, Esther sought to formalize the concepts of DST, creating a dialogue between formal theory and empirical work. Her initial discussions with Scott Kelso led her to a relative phase model of rhythmic movements, but it was her collaboration with Gregor Schöner and their work on the DFT that solidified the theory–experiment link. This link produced two formal models of classic findings in infant cognition

(Schöner & Thelen, 2006; Thelen et al., 2001) and has led to a host of innovations in other domains (e.g., Bastian, Schöner, & Riehle, 2003; Erlhagen & Schöner, 2002; Schutte, Spencer, & Schöner, 2003; Spencer & Schöner, 2003; Spencer, Simmering, & Schutte, 2006).

Although Esther had immense enthusiasm for formal theoretical work, she always emphasized the reciprocal interaction among different scientific approaches to the study of development. She refused to invest too heavily in a particular mathematical model, preferring to emphasize the importance of conceptual thinking, telling a good story, and having a good metaphor: ''the role of formal models is to make . . . underlying assumptions extremely precise. The specific form of the model is, thus, less important than the general principles of development on which it is based'' (Thelen & Bates, 2003, p. 378).

This emphasis came through in the clarity of her writing and the clarity of her thought. As an example, in a wonderful article targeted toward undergraduates entitled ''The Improvising Infant: Learning about Learning to Move,'' Esther compared development to improvisational jazz (Thelen, 1998). She discussed how infants create new solutions step by step over development as they carve out their own unique pathway. Thus, development is more like improvisational jazz, with the infant as a musician and less like a mechanistic process driven by genes. And, as with jazz, the music infants create as they learn to move and explore must be considered as a whole pattern rather than a sequence of individual notes. Note that Esther actually brought a variant of this metaphor into reality by collaborating with Helga Winold to study the dynamics of expertise in cello performance (Winold, Thelen, & Ulrich, 1994).

A New Grand Theory of Development

Given Esther's emphasis on general developmental processes, we can ask where the two trajectories of her career led. The answer is that they led to a new grand theory of development, DST. Four central concepts of the theory emerged across Esther's career and have been evident in the examples mentioned previously. First, DST creates *a new emphasis on time*—behavior emerges in the moment, but the effects of each behavioral decision accumulate over longer time scales, as each change sets the stage for future changes. This theme is evident in Esther's many detailed longitudinal studies showing a cascade of influences over different time scales (e.g., Thelen & Ulrich, 1991; Thelen et al., 1993). Second, according to DST, *behavior is multiply determined and softly assembled* from the nonlinear interactions of multiple subsystems. The concept of soft assembly is beautifully illustrated in some of Esther's earliest work. For example, in her work on the disappearing steps, Esther showed how stepping patterns come and go depending on the weight of the infant's legs, whether the infant is in water or not, whether the infant is upright, lying down, and so on (e.g., Thelen et al., 1984). Note that this concept of soft assembly is critical to allow the child to act in a changing and variable world. Moreover, soft assembly provides a natural foundation for exploration and selection because behavioral patterns are not fixed, but varying and flexible.

The third central concept of DST is *embodiment*—perception, action, and cognition form an integrated system that cannot be partitioned. Esther and Linda Smith emphasized this latter point in their 1994 book: ''We, like the symbolic computational theorist, view cognition as all one kind; but in our view, it is all embodied, all distributed, all activity, all a complex event in time'' (Thelen & Smith, 1994, p. 337). The embodiment of behavior is, perhaps, best illustrated in the weighted limbs studies using the A-not-B task: by simply changing the feel of the arms between the A and B trials, Esther and her colleagues could create perseverative or accurate responding in the task (Diedrich, Clearfield, Smith, & Thelen, 2005). Fourth, DST shows a new respect for *individuality*. Development happens in individual children solving individual problems in their own unique ways. This theme is beautifully illustrated in the story of Gabriel and Hannah learning to reach (e.g., Thelen et al., 1996).

Putting these themes together, we can sketch the view of development that Esther championed (see Figure 7). We start with a child-in-context composed of multiple components at different levels of an integrated system. These components include neural dynamics captured by the DFT (Bastian, Riehle, Erlhagen, & Schöner, 1998; Erlhagen, Bastian, Jancke, Riehle, & Schöner, 1999; Jancke et al., 1999; Thelen et al., 2001), neural oscillations critical to motor control and rhythmic actions (Kelso, 1995), the spring-like characteristics of muscles (e.g., Thelen & Ulrich, 1991), and so on. Critically, these components are fully embodied and reciprocally coupled (see the bidirectional arrows in Figure 7). Moreover, they are coupled together in a softly assembled way that is grounded in the sensorimotor world.

What happens, then, as the child interacts with the world from second to second, minute to minute, situation to situation? Over short time scales, learning occurs. What is learning from a dynamic systems

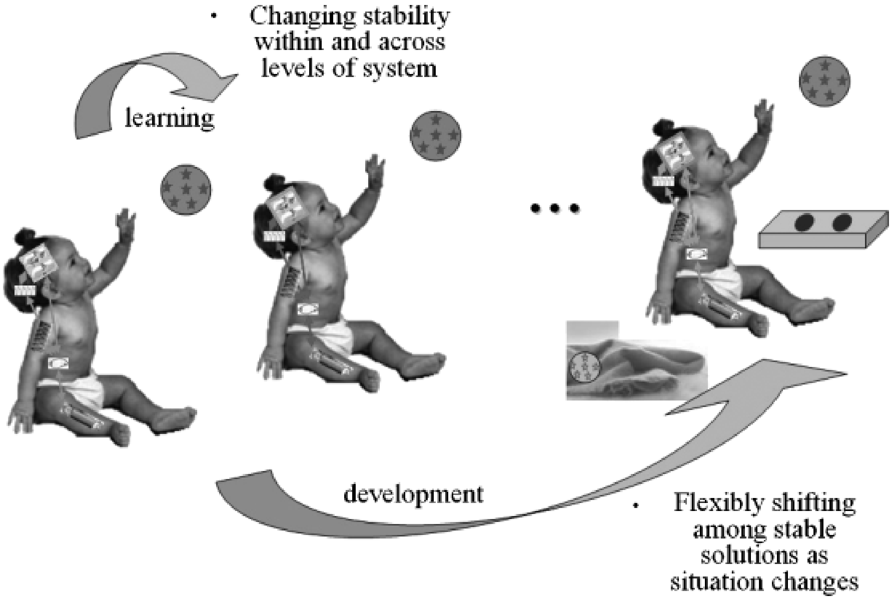

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Figure 7. A depiction of learning and development from a dynamic systems perspective. Each image of the infant captures one time point in learning/development with time moving from left to right. The infant is viewed as an integrated system consisting of multiple, reciprocally coupled components (see the bidirectional arrows) embedded within a specific context. The components depicted include neural dynamics (captured by the simulation of the dynamic field theory in the infant's head), oscillatory dynamics (see oscillation in the brain and spinal cord), and the springy character of muscles (see springs in the arm and leg). Learning is about changing stability within and across levels. This is illustrated by the green highlight around the simulation in the infant's head, and the shift from blue arrows in the first learning step to red arrows in the second. Development is about flexibly shifting among stable solutions, that is, being able to flexibly shift from the dynamic organization needed to reach for the ball, to the dynamic organization needed to reach for the box, to the dynamic organization needed to grab the blanket to slide the ball forward.

view? At a general level, the infant is carving out individual solutions to the real-world problem she is facing, in this case, grabbing an attractive ball (see Figure 7). In dynamic systems concepts, she is forming stable attractors or patterns. Such stability can emerge at one level—for instance, at the level of neural dynamics captured by the DFT—or stability can be reflected in changes in the coupling of components (see the red arrows in Figure 7). Importantly, though, stability is not an end-state—there is always a delicate balance between stability and instability. This allows for improvisation on a theme; for the infant to use stable solutions, and to also discover novel solutions that arise through exploration and often through accident.

Moving forward, these real-time and learning-time processes are integrated over longer time scales to form a unique developmental trajectory. Here, the infant continues to carve out stable solutions, and she learns to flexibly shift from one solution to another as the situation or her motivations change. Thus, she can flexibly shift from one stable pattern when reaching for the ball, to another stable pattern when confronted with two identical hiding locations in an A-not-B situation, to another stable pattern as she has to reach for the blanket to retrieve the ball (see Figure 7). Note that these solutions are particular to this child and this developmental trajectory is unique to this child. Nevertheless, the processes that work over these time scales are general.

Esther conveyed her excitement about this view of development in her 1994 book with Linda Smith: ''What can a dynamic approach do? A dynamic approach can change the way you think about development and it can change the way you conduct research in development. Once we began to view development from a dynamic and selectionist approach, we found the ideas so powerful that we could never go back to other ways of thinking. Every paper we read, every talk we heard, every new bit of data from our labs took on new meaning . . . The final test of dynamics in development, of course, is in its usefulness to a wide range of scholars. We hope readers will accept the challenge of the new way of thinking and working and we look forward to the report card'' (Thelen & Smith, 1994, pp. 341–342).

Looking to the Future: Challenges for a Dynamic Systems Approach

As with all grand theories, there are many challenges that lie ahead. We highlight two that were emerging as critical next steps in Esther's work. The first challenge is to create dynamical systems that *change themselves* and, in this way, begin to integrate the multiple time scales of development. Here, Esther thought dynamical systems theorists might borrow insights from connectionist approaches to learning (for related ideas, see Spencer & Thelen, 2003; Spencer, Thomas, & McClelland, in press). Nevertheless, Esther thought that learning extended beyond what could be captured by accumulating the statistics of experience. Rather, she thought a new view of learning might emerge by integrating insights from connectionism with the rich understanding of real-time dynamics she and her colleagues explored (e.g., Schöner & Thelen, 2006; Thelen et al., 2001). Esther also thought that developmental scientists might gain insights about integrating time scales by looking into the field of developmental robotics to discover the contingencies that may structure the learning experience of the perceiving and acting infant.

A second challenge facing DST is to develop dynamic systems that *create themselves* through processes of exploration and selection. The theme of exploration and selection was present in Esther's work quite early and played a central role in her 1994 book with Linda Smith. There, they incorporated Gerald Edelman's ''neural Darwinism'' (see Edelman, 1987) to understand how nervous systems can create new insights about the world via the redundant, degenerate neural signals that underlie experience. To date, however, it is not clear how to integrate this view with, for instance, the richly structured behavioral dimensions and neural dynamics that underlie the DFT (Thelen et al., 2001). Moreover, a critical challenge with selectionist ideas is to understand generalization—how the novel associations and insights created in-the-moment are integrated together to extend across situations. Esther thought that action might provide a common link across diverse experiences, given the embodiment of cognition and the fact that the body is always present, shaping and structuring experience.

Looking to the Future: Reaching Out

Another kind of challenge is to reach out and bring DST into the world. There are two senses in which this needs to be done. First, Esther thought that DST needed a richer sense of action in the real world to capture the emotional and motivational side of development. Thus, there must be more than toys and treadmills in the child's world (see Figure 7); we must add mothers and fathers and consider the influences of whole families and large social and cultural groups (for steps in this direction, see Fogel, Nwokah, Dedo, & Messinger, 1992; Lewis, 2000). Second, Esther sought a stronger emphasis on dialog with parents, practitioners, and policymakers to translate theory into practice with infants, children, and adults needing assistance. Thus, Esther sought to take her knowledge of empirical findings, conceptual theory, and formal theory and bring it to the level of individual children in the world.

We have already mentioned two of Esther's translational projects: working with physical and occupational therapists to improve the lives of, for instance, children with Down syndrome (Ulrich et al., 2001) and working with musical scholars to study the development of expertise in the training of cellists (Winold et al., 1994). A third translational effort played a central role in the final phase of Esther's career: she became a *Guild Certified Feldenkrais Practitioner*$^{\text{CM}}$. Here, she asked whether the principles of DST that shed light on motor development could foster a deeper understanding of the *Feldenkrais Method*$^{®}$ of somatic education. Importantly, she did not view this translational project as a one-way flow of information from researchers to the applied world. Rather, she had a vision of reciprocal dialog—that practitioners could gain theoretical grounding, but basic researchers could gain insights into the generality of ideas as well as novel insights into developmental process.

Why was Esther drawn to the *Feldenkrais Method*? The *Feldenkrais Method* uses subtle variation, innovation, and explicit differentiation of the perception of movements to free people from habitual patterns and allow new movement solutions to emerge. Thus, *Feldenkrais* practitioners introduce novel and/or difficult movement problems to help bring movement perception into awareness. This also serves to foster new modes of coordination and to destabilize old habits, allowing the discovery of new ways to move. To Esther and to many others, this view of movement education has a natural affinity with concepts of DST (Buchanan & Ulrich, 2001). Thus, toward the end of her career, Esther began to conduct research studies on the effects of the *Feldenkrais Method* on healthy adults; she participated in and organized symposia to promote dialog among researchers and *Feldenkrais* practitioners; and she looked forward to a second career giving *Feldenkrais* lessons to infants and children. Sadly, this second career was not realized, but Esther's efforts to reach out and bring dynamic systems concepts into the world continue.

We end with Esther's own words—with a transcript from a conversation between Roger Russell (a *Certified Feldenkrais Trainer*) and Esther that took place in Amsterdam in 1998. In this interview, Esther expresses the pleasure she received from translating dynamic systems ideas to others and her vision of the future. Central to this vision was the hope that her theoretical ideas would be useful, not just to researchers in the field of child development, but to people *in general*. That is, she hoped these ideas would have a profound effect on the way people think about development, as well as how they think of themselves—as embodied, grounded, ever-changing, ever improvising people in the world.

> Roger Russell: ''You've been involved in the academic field where most of the people who listen to you are other academics asking academic questions.''
> Esther Thelen: ''I've actually talked to a lot of practitioners of various kinds.''
> Roger Russell: ''What interests them [the practitioners] in what you're saying?''
> Esther Thelen: ''I think that people dealing with adults and children who have some sort of problem . . . children with speech problems, with motor problems, adults with problems, emotional and so on, are now really very interested in the parallels . . . between the processes of change as they occur in development and the processes of change as they may happen in some sort of educational or therapeutic encounter. And a lot of people have told me that they're looking for some theoretical basis for what they do. I've had this happen over and over where people will come up to me and say, 'well, this is very interesting and you are describing perfectly what I do in my speech therapy!' or 'what I do in my psychotherapy—this is how I approach therapy! But I have not had a theoretical kind of rationale for it before [that is] so explicit about how people change.'
> So, to have it spelled out as a developmental process—I think it's very honest to put change, dysfunctional outcomes and functional outcomes all in the same vocabulary. In other words, people are . . . looking for models that are not just medical models of how things go badly and how you change them. And the implications of the kinds of ways that we're thinking are that you may have dysfunctional outcomes out of the same processes—developmental processes—that led to more adaptive outcomes . . . Therefore, you can look toward developmental processes to think about how to move people beyond their . . . maladaptive ways of interacting either in relationships or in their skills or so on. So I think that's been quite attractive and I'm pleased, if, in fact, this will happen that these things will come together.''
> Roger Russell: ''What pleases you about it?''
> Esther Thelen: ''Well, it's nice to know that something that you've done and that your colleagues and your students have done actually may be useful to someone, other than just, you know, giving your papers to other academics!
> And especially . . . if it will inspire therapists to think differently and maybe try new things. I think that would be a lovely way of translating basic laboratory and theoretical work. I started in this field because I'm interested in how things work. I want to know, 'gee, why does it change like this? What happens?' without much thought of, well, is this useful to anyone. Basic, just basic scientific curiosity. But, if at the same time it turns out that it can be useful at least a little bit, then that's wonderful!''

References

Andre-Thomas, & Autgaerden, S. (1966). Locomotion from pre- to postnatal life. In S. Society (Ed.), *Clinics in developmental medicine* (*Vol. 24*). London: William Heinemann.

Angulo-Barroso, R. M., Ulrich, D. A., & Tiernan, C. (2004, March). *Motor activity and adapted treadmill stepping patterns in infants born at risk for cerebral palsy*. Paper presented at the Gatlinburg Conference, San Diego, CA.

Bastian, A., Riehle, A., Erlhagen, W., & Schöner, G. (1998). Prior information preshapes the population representation of movement direction in motor cortex. *NeuroReport*, *9*, 315–319.

Bastian, A., Schöner, G., & Riehle, A. (2003). Preshaping and continuous evolution of motor cortical representations during movement preparation. *European Journal of Neuroscience*, *18*, 2047–2058.

Bjork, E. L., & Cummings, E. M. (1984). Infant search errors: Stage of concept development or stage of memory development. *Memory and Cognition*, *12*, 1–19.

Bremner, J. G. (1978). Spatial errors made by infants: Inadequate spatial cues or evidence of egocentrism? *British Journal of Psychology*, *69*, 77–84.

Buchanan, P. A., & Ulrich, B. D. (2001). The *Feldenkrais Method*®: A dynamic approach to changing motor behavior. *Research Quarterly for Exercise and Sport*, *72*, 315–323.

Bushnell, E. (1985). The decline of visually guided reaching during infancy. *Infant Behavior and Development*, *8*, 139–155.

Butterworth, G., Jarrett, N., & Hicks, L. (1982). Spatiotemporal identity in infancy: Perceptual competence or conceptual deficit? *Developmental Psychology*, *18*, 435–449.

Clearfield, M. W., Diedrich, F. J., Smith, L. B., & Thelen, E. (2006). Piaget was right: Thoughts close to the sensorimotor surface, Manuscript in preparation. Q3

Clearfield, M. W., Dineva, E., Smith, L. B., Diedrich, F. J., & Thelen, E. (2006). Cue salience and memory in infant perseverative reaching: A test of the Dynamic Field Model, Manuscript under review. Q4

Clearfield, M. W., Smith, L. B., Diedrich, F. J., & Thelen, E. (2006). Young infants reach correctly on the A-not-B task: On the development of stability and perseveration. *Infant Behavior and Development*, *29*, 435–444.

Clearfield, M. W., & Thelen, E. (2001). Stability and flexibility in the acquisition of skilled movement. In C. Nelson (Ed.), *Handbook of developmental cognitive neuroscience* (pp. 253–266). Cambridge, MA: MIT Press.

Corbetta, D., & Thelen, E. (1994). Shifting patterns of interlimb coordination in infants' reaching: A case study. In S. P. Swinnen, H. Heuer, J. Massion, & P. Casaer (Eds.), *Interlimb coordination: Neural, dynamical, and cognitive constraints* (pp. 413–438). San Diego: Academic Press.

Corbetta, D., & Thelen, E. (1996). The developmental origins of two-handed coordination: A dynamic perspective. *Journal of Experimental Psychology: Human Perception and Performance*, *22*, 502–522.

Corbetta, D., & Thelen, E. (1999). Lateral biases and fluctuations in infants' spontaneous arm movements and reaching. *Developmental Psychobiology*, *34*, 237–255.

Corbetta, D., & Thelen, E. (2002). Behavioral fluctuations and the development of manual asymmetries in infancy: Contribution of the dynamic systems approach. In S. J. Segalowitz & I. Rapin (Eds.), *Handbook of neuropsychology (Vol. 8): Child neuropsychology, Part I* (pp. 309–328). Amsterdam: Elsevier Science Publishing Co.

Diedrich, F. J., Clearfield, M. W., Smith, L. B., & Thelen, E. (2005). *Motor memory influences performance in the A-not-B task: Effects of arm-loading and posture*. Unpublished manuscript.

Diedrich, F. J., Highlands, T., Thelen, E., & Smith, L. B. (2001). The role of target distinctiveness in infant perseverative reaching errors. *Journal of Experimental Child Psychology*, *78*, 263–290.

Diedrich, F. J., Thelen, E., Smith, L. B., & Corbetta, D. (2000). Motor memory is a factor in infant perseverative errors. *Developmental Science*, *3*, 479–494.

Edelman, G. M. (1987). *Neural Darwinism*. New York: Basic Books.

Erlhagen, W., Bastian, A., Jancke, D., Riehle, A., & Schöner, G. (1999). The distribution of neuronal population activation (DPA) as a tool to study interaction and integration in cortical representations. *Journal of Neuroscience Methods*, *94*, 53–66.

Erlhagen, W., & Schöner, G. (2002). Dynamic field theory of movement preparation. *Psychological Review*, *109*, 545–572.

Fischer, K. W., & Bidell, T. R. (1998). Dynamic development of psychological structures in action and thought. In W. D. (Editor-in-Chief) & R. M. Lerner (Eds.), *Handbook of child psychology (5th ed.) Vol. 1: Theoretical models of human development* (pp. 467–561). New York: Wiley. Q5

Fogel, A., Nwokah, E., Dedo, J. Y., & Messinger, D. (1992). Social process theory of emotion: A dynamic systems approach. *Social Development*, *1*, 122–142.

Gopnik, A. (1996). The post-Piaget era. *Psychological Science*, *7*, 221–225.

Heriza, C. (1988). Organization of leg movements in preterm infants. *Physical Therapy*, *68*, 1340–1346.

Jancke, D., Erlhagen, W., Dinse, H. R., Akhavan, A. C., Giese, M., Steinhage, A., et al. (1999). Parametric population representation of retinal location: Neuronal interaction dynamics in cat primary visual cortex. *Journal of Neuroscience*, *19*, 9016–9028.

Kelso, J. A. S. (1995). *Dynamic patterns: The self-organization of Brain and behavior*. Cambridge: The MIT Press.

Kelso, J. A. S., Holt, K. G., Kugler, P. N., & Turvey, M. T. (1980). On the concept of coordinative structures as dissipative structures: II. Empirical lines of convergence. In G. E. Stelmach & J. Requin (Eds.), *Tutorials in motor behavior* (pp. 49–70). New York: North Holland.

Kelso, J. A. S., & Tuller, B. (1984). A dynamical basis for action systems. In M. S. Gazzaninga (Ed.), *Handbook of cognitive neuroscience* (pp. 321–356). New York: Plenum.

Lewis, M. D. (2000). The promise of dynamic systems approaches for an integrated account of human development. *Child Development*, *71*, 36–43.

Mandler, J. M. (1988). How to build a baby: On the development of an accessible representational system. *Creative Development*, *3*, 113–136.

Marcovitch, S., & Zelazo, P. D. (1999). The A-not-B error: Results from a logistic meta-analysis. *Child Development*, *70*, 1297–1313.

Munakata, Y. (1998). Infant perseveration and implications for object permanence theories: A PDP model of the AB task. *Developmental Science*, *1*, 161–184.

Oppenheim, R. W. (1981). Ontogenetic adaptations and retrogressive processes in the development of the nervous system and behaviors: A neuroembryological perspective. In H. F. R. Prechtl & K. Connolly (Eds.), *Maturation and development: Biological and psychological perspectives* (pp. 73–109). Philadelphia: Spastics International Medical Publications by William Heinemann Medical Books.

Peiper, A. (1963). *Cerebral function in infancy and childhood*. New York: Consultants Bureau.

Piaget, J. (1954). *The construction of reality in the child*. New York: Basic Books.

Schöner, G., & Thelen, E. (2006). Using dynamic field theory to rethink infant habituation. *Psychology Review*, *113*, 273–299.

Schutte, A. R., Spencer, J. P., & Schöner, G. (2003). Testing the dynamic field theory: Working memory for locations becomes more spatially precise over development. *Child Development*, *74*, 1393–1417.

Smith, L. B., Thelen, E., Titzer, R., & McLin, D. (1999). Knowing in the context of acting: The task dynamics of the A-not-B error. *Psychological Review*, *106*, 235–260.

Spelke, E. S. (1998). Nativism, empiricism, and the origins of knowledge. *Infant Behavior and Development*, *21*, 181 – 200.

Spencer, J. P., & Schöner, G. (2003). Bridging the representational gap in the dynamical systems approach to development. *Developmental Science*, *6*, 392 – 412.

Spencer, J. P., Simmering, V. R., & Schutte, A. R. (2006). Toward a formal theory of flexible spatial behavior: Geometric category biases generalize across pointing and verbal response types. *Journal of Experimental Psychology: Human Perception and Performance*, *32*, 473 – 490.

Spencer, J. P., & Thelen, E. (2000). Spatially specific changes in infants' muscle co-activity as they learn to reach. *Infancy*, *1*, 275 – 302.

Q6 Spencer, J. P., & Thelen, E. (2003). Connectionism and dynamic systems theory: Are these really different approaches to development? *Developmental Science* (Special Issue).

Q7 Spencer, J. P., Thomas, M. S., & McClelland, J. L. (in press) *Toward a new grand theory of development? Connectionism and dynamic systems theory re-considered*. New York: Oxford University Press.

Spencer, J. P., Vereijken, B., Diedrich, F. J., & Thelen, E. (2000). Posture and the emergence of manual skills. *Developmental Science*, *3*, 216 – 233.

Thelen, E. (1979). Rhythmical stereotypies in normal human infants. *Animal Behaviour*, *27*, 699 – 715.

Thelen, E. (1981a). Kicking, rocking, and waving: Contextual analysis of stereotyped behaviour in normal infants. *Animal Behaviour*, *29*, 3 – 11.

Thelen, E. (1981b). Rhythmical behavior in infancy: An ethological perspective. *Developmental Psychology*, *17*, 237 – 257.

Thelen, E. (1985). Developmental origins of motor coordination: Leg movements in human infants. *Developmental Psychobiology*, *18*, 1 – 22.

Thelen, E. (1998). The improvising infant: Learning about learning to move. In J. S. DeLoache, S. C. Mangelsdorf, & E. Pomerantz (Eds.), *Current readings in child development* (3rd ed., pp. 26 – 42). Boston: Allyn and Bacon.

Thelen, E. (2000). Motor development as foundation and future of developmental psychology. *International Journal of Behavioral Development*, *24*, 385 – 397.

Thelen, E., & Bates, E. A. (2003). Connectionism and dynamic systems: Are they really different? *Developmental Science*, *6*, 378 – 391.

Thelen, E., & Corbetta, D. (1994). Exploration and selection in the early acquisition of skills. *International Review of Neurobiology*, *37*, 75 – 102.

Thelen, E., Corbetta, D., Kamm, K., Spencer, J. P., Schneider, K., & Zernicke, R. F. (1993). The transition to reaching: Mapping intention and intrinsic dynamics. *Child Development*, *64*, 1058 – 1098.

Thelen, E., Corbetta, D., & Spencer, J. P. (1996). The development of reaching during the first year: The role of movement speed. *Journal of Experimental Psychology: Human Perception and Performance*, *22*, 1059 – 1076.

Thelen, E., & Farish, D. J. (1977). An analysis of the grooming behavior of wild and mutant strains of *Bracon hebetor* (Braconidae: Hymenoptera). *Behaviour*, *62*, 699 – 715.

Thelen, E., Fisher, D. M., & Ridley-Johnson, R. (1984). The relationship between physical growth and a newborn reflex. *Infant Behavior and Development*, *7*, 479 – 493.

Thelen, E., Kelso, J. A. S., & Fogel, A. (1987). Self-organizing systems and infant motor development. *Developmental Review*, *7*, 39 – 65.

Thelen, E., Schöner, G., Scheier, C., & Smith, L. B. (2001). The dynamics of embodiment: A field theory of infant perseverative reaching. *Behavioral and Brain Sciences*, *24*, 1 – 86.

Thelen, E., & Smith, L. B. (1994). *A dynamic systems approach to the development of cognition and action*. Cambridge: MIT Press.

Thelen, E., & Ulrich, B. D. (1991). Hidden skills: A dynamic systems analysis of treadmill stepping during the first year. *Monographs of the Society for Research in Child Development*, *56* (1, Serial No. 223).

Touwen, B. (1976). *Neurological development in infancy*. London: Spastic International Medical Publishers.

Ulrich, B. D., & Moerchen, V. (2005). *Infants with spina bifida: Body weight supported treadmill stepping over the first postnatal year*. Paper presented at the Motor development and learning in infancy II: Fundamental concepts and applications, Murcia, Spain.

Ulrich, D. A., Ulrich, B. D., Angulo-Barroso, R. M., & Yun, J.-K. (2001). Treadmill training of infants with Down syndrome: Evidence-based developmental outcomes. *Pediatrics*, *108*, 1 – 7.

van der Maas, H. L. J., Dolan, C. V., Grasman, R. P. P., Wicherts, J. M., Huizenga, H. M., & Raijmakers, M. E. J. (in press) A dynamical model of general intelligence: The positive manifold of intelligence by mutualism. *Psychological Review*. Q8

Van Geert, P. (1998). A dynamic systems model of basic developmental mechanisms: Piaget, Vygotsky, and beyond. *Psychological Review*, *105*, 634 – 677.

Wellman, H. M., Cross, D., & Bartsch, K. (1987). Infant search and object permanence: A meta-analysis of the A-not-B error. *Monographs of the Society for Research in Child Development*, *51*, 1 – 51.

Winold, H., Thelen, E., & Ulrich, B. D. (1994). Coordination and control in the bow arm movements of highly skilled cellists. *Ecological Psychology*, *6*, 1 – 31.