Time-Scale Dynamics and the Development of an Embodied Cognition

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EDITORS' INTRODUCTION

Cognition is in many ways an emergent phenomenon. Mature cognitive systems are the result of a long and always ongoing process of self-organization and adaptation, and if we really want to fully understand the nature of the mature system we must see it in this context. One of the strengths of the dynamical approach to cognition is its ability to describe the emergence of complex structures and processes. Consequently, the first of the applications-oriented chapters in this book is a sweeping view of cognitive development from a dynamical perspective.

As a developmental psychologist, Esther Thelen’s immediate concern is with questions such as: How do infants acquire such seemingly simple skills as reaching out and grasping an object? She finds that dynamics provides the best framework within which to formulate specific answers, but it also provides much more. Thelen argues that taking up the dynamical perspective leads to dramatic reconceptualization of the general nature of cognitive development, and indeed of the product of development, mind itself.

Laying the foundation for these ambitious claims are highly detailed developmental studies. In this chapter Thelen describes two sets of studies, one of reaching and grasping, and another of coordinated kicking. Both are cases of infants acquiring control over the forceful interactions of their bodies with their environments. Dynamics provides a powerful vocabulary for describing these developmental processes. Changes in behavior come to be understood in terms of attractors, stability, potential wells, parameter adjustment, and so forth. Taking over this vocabulary facilitates a whole new way of seeing how sophisticated capacities emerge. New abilities take shape in a process of gradual adjustment of the dynamics governing the range of movements currently available; this adjustment is effected by exploratory activity itself. Since infants can begin this process of adjustment from very different starting points, it is highly unlikely that there is any predetermined, genetically coded program for development. It is rather a self-organizing process in which solutions emerge to problems defined by the particular constraints of the infant’s immediate situation.

How does this connect with the nature of cognition and mind? Thelen adopts the Piagetian perspective that “thought grows from action and that activity is the engine
of change." At the same time, however, she rejects Piaget’s conception of the endstate of cognitive development as an objective mind reasoning about the world by means of abstract logical structures. This "objectivist" conception of mind has recently been challenged by philosophers and cognitive scientists who insist that mind is fundamentally embodied, and, in particular, that the bodily experience of force is essential to thought and language. Consequently, to understand how infants come to be able to control the forceful interactions of their bodies with their environment is to gain insight into the nature of cognitive processes as they emerge. A dynamical perspective on development, according to which change occurs at many time scales, and change at one scale shapes and is shaped by change at others, thus provides a general framework within which to understand the origin and nature of embodied cognition, and in this sense, to help resolve the problem of the relation of mind to body.

3.1 INTRODUCTION

As this book attests, the concepts and tools of dynamical systems offer powerful and perhaps revolutionary ways of understanding human cognition. For nearly half a century, the dominant metaphor for understanding mind, brain, and behavior has been that of information processing, a metaphor based on serial computation. Dynamics has the potential, I believe, to supplant this accepted view with new principles that are more biologically plausible and yet apply across many levels of mental phenomena.

The implications of adopting a noncomputational view of mind are profound and widespread. Such a view challenges long-held and cherished constructs such as symbolic representation, the modularity of knowledge, and the distinction between knowledge and performance. But dynamics also holds great promise for understanding some of the most recalcitrant issues in the mind sciences. These may include such problems as the origins of novelty in brain and behavior, the sources of individual differences, the nature of category formation, and the fluid and context-sensitive aspects of human behavior (see Smith and Thelen, 1993; Thelen and Smith, 1994).

One of the most persistent issues in the brain-mind sciences is that of mind-body dualism. What is the relation between the abstract and reflective mind and the qualities of the flesh and of the world in which mind sits? How can these two levels coexist in the same individual? Is there a connection between the domains of biology and physics and those of mind and cognition? Such questions have plagued philosophers and psychologists for millennia, and still do. As Searle (1992) wrote, "... there really has been only one major topic of discussion in the philosophy of mind for the past fifty years or so, and that is the mind-body problem" (p. 29).

I suggest here that a dynamical systems analysis can offer insights into this "major topic of discussion." I argue that understanding transactions between body and mind should begin with a developmental analysis based on dynamics, the study of processes that are continuous in time. In particular, if we can show continuities in time between the physical and the mental—that they

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share the same dynamics—we can bridge the gulf between the traditional duality of levels, body and mind. To understand continuities in time, we must look toward development, growth, and change within an individual’s life span. Toward this goal, I will argue, as have other developmental psychologists before me, that the mundane physical events of infancy are indeed the very foundations of thinking, the uniquely human way of adapting to the world. But I want to go further. I will also claim that the way in which infants acquire seemingly simple body skills supports a particular view of human cognition, thinking grounded in and inseparable from bodily action. That thought is thus embodied—containing within it the very essence of our bodily experience—flows directly from considering minds’ origins and from the assumption that the time scales of processes at different levels are tightly interwoven. There can be no discontinuities in processes that occur over time. What infants do in everyday life, what they perceive, how they act, and what they remember are joined seamlessly to how they think. Since a major developmental task of infancy is gaining control of the body, cognition is thus embodied as its origins deal with actions of the body in the world. Thus, since the processes of perceiving and acting and the processes of thinking continue to share the same time-scale dynamics, they cannot be separated in levels. Mind and body are united at the beginning of life and nowhere along life’s path do their processes split asunder.

### 3.2 Models and Metaphors

My line of reasoning depends on taking seriously the evocative title of this book, *Mind as Motion*. What the editors had in mind, I believe, was to portray mental activity not as a structure of static representations, but as flow through time. An apt metaphor in this case is a mountain stream flowing over a rocky bed. Both the global course of the stream and its local whirls and eddies emerge from the architecture of the streambed and the force of the water flow, but are in no way programmed by those constraints. The pattern of a whirlpool may be quite stable as long as the water pressure and streambed do not change. Or a new pattern may form in response to a stray rock entering the bed or after a heavy rain. The eddy itself is not symbolically represented anywhere, yet it contains within it both its past history—the melting of the snow on the mountain and the configuration of the bed up-stream—and its immediate constraints.

Under particular laboratory conditions, the behavior of water flow and turbulence can be mathematically captured by systems of nonlinear dynamical equations. Indeed the science of dynamical systems is preeminently a mathematical science, born from just such problems of understanding complex and time-based processes as patterns of flow. But whether or not our particular mountain stream can, in practice, be mathematically described by us does not alter the fundamental truth of its existence, that pattern lives in flow and lives only in flow.
Because mathematical modeling has also been a dominant tradition in the cognitive sciences, there is a seductive danger of appropriating the mathematics of dynamical systems with insufficient consideration of their fundamental truths. Fitting dynamical equations to behavioral data and simulating behavior with dynamical models are critical steps in our understanding. But to adopt mathematical dynamics without acknowledging the radical implications of a truly dynamical cognition reduces dynamics to just another model du jour, or at worst, a redescription of the prevailing structural and computational state of affairs. Along with the mathematical language of dynamics, must come, I believe, the fundamental assumption that pattern only emerges in process, and thus a rejection of symbols, structures, and stages as “things” that live in the head. I will also argue here that a dynamical approach erases the traditional boundaries of mental life. There can be no description of a purely “inner life”: every mental and behavioral act is always emergent in context, just as are the eddies in the stream. Perception, action, and cognition form a single process, with no distinction between what people really “know” and what they perform. There are no distinctions between acting, learning, and developing; processes of change all live within a single, nested time scale.

3.3 SOME BACKGROUND ON THE DEVELOPMENT OF BODY AND MIND

I think the best way to put some life into these abstractions is to explain the conventional wisdom about the relation of the simple motor skills of infancy and the emergence of thought. Until quite recently motor skill development was seen as a necessary, but psychologically uninteresting part of infant development. Textbooks routinely published (most still do) illustrations and explanations of the stagelike emergence of the major “motor milestones” such as rolling over, sitting up, crawling, and walking. The message these texts delivered was the amazing orderliness and universal character of the unfolding skills. This view of development came directly from the work of Arnold Gesell and Myrtle McGraw in the 1930s and 1940s, who described these stages in great detail (see, e.g., McGraw, 1940; Gesell and Ames, 1940). More important was their developmental account: the ordered progression of the emergence of skills reflected the maturation of the brain. They believed that motor coordination and control was a product of autonomous brain development, which happened as infants got older. Although some contemporary developmentalists still invoke maturation as a developmental mechanism, there is no evidence that the brain autonomously matures from codes in the genes, and like an independent executive, causes the body to obey.

Unwittingly perhaps, these early pioneers fostered a profoundly dualistic view. They envisioned motor development as thoroughly biological and encapsulated. Although infants’ skills reflected changes in the brain, such skills were not part of mind in any way. In fact, Gesell himself disdained mentalistic descriptions and preferred to stick exclusively with observables in posture and many do in the fi...
and movement. What has come through in the textbooks, and in the minds of many developmentalists, is that the biological side of human existence lives in the first few chapters, and having dispensed with our biological side, we can now move on to more interesting chapters.

3.4 THE PIAGETIAN LEGACY

It was the seminal developmental theorist Jean Piaget who made developmentalists consider another approach: that thought grows from action and that activity is the engine of change. Piaget believed that infancy—the sensorimotor period, he called it—formed the foundation of cognition through building the mental structures in which higher thought was embedded. Piaget (1952) described his own infants with brilliance and understanding, surely the best developmental descriptions ever written. In his words, even the baby’s simple acts—sucking and batting, looking and smiling—took on profound meaning. According to Piaget, mental life was truly constructed through the combination and change of these simple acts.

Where I and many other contemporary developmentalists differ from Piaget is not in his account of the seamless connections between action and thought, but in the very nature of mind that is the product of this developmental process. Piaget believed that human cognition was a biological adaptation designed to know the truths about the world by logical structures. He wanted to understand how people acquired and perfected these logical structures during development. Piaget made several assumptions that may be challenged by a dynamic cognition—first, that there are logical relations in the world to be discovered, and second, that people symbolically represent these relations in mind through a series of propositional structures.

Readers may recall that in the typical Piagetian developmental sequence of understanding, say, objects or space, young infants are prisoners of their immediate perceptions and they cannot escape the boundaries of their bodies. They do not understand, for example, that an object still exists when it is hidden from sight, or that the window stays in the same place when they rotate their bodies. According to Piaget, therefore, infants and children must shed their subjective, context-grounded, illogical, and embodied solutions for the ideal abstractions of formal logic. That is, real cognition means rising above the here-and-now of bodily existence, of perception and action in the world, to a level of pure symbol manipulation, as development proceeds inexorably toward real cognition. Thus, although Piaget broke from the maturationists and gave experience a preeminent role as a developmental mechanism, he retained their fundamental dualism.

3.5 ALTERNATIVES TO MIND-BODY DUALISM

Although rarely recognized or acknowledged, some form of mind-body dualism is a continuing assumption behind, and the consequence of much contem-
porary cognitive science. Cognitive models that seek to represent an objective and knowable world with formal systems of symbols, logic, and computation have been termed \textit{objectivist} (Johnson, 1987; Lakoff, 1987), \textit{materialist} (Searle, 1992), and \textit{cognitivist} (Varela, Thompson, and Rosch, 1993). These critics point out that two kinds of profound dualism result from assuming that the world is understood through propositional logic or computational structures or that mind is at core rational, encapsulated, abstract, and a priori. The first is the denial of the relevance of the physical body in all its instantiations through movement, feeling, and emotion. The second is the separation of intelligent behavior from the subjective self, from consciousness, imagination, and from commonsense understanding. In both cases, these critics argue, cognitivist models are divorced from major and essential aspects of human experience.

There is a new, but growing, challenge to rational and propositional views of mind. These thinkers reject the assumption that minds work like digital computers. They suggest that knowing—categorizing the world, acting in it, giving the world meaning, and reflecting upon our acts—is at core non-propositional, fluid, messy, imaginative, personal, emergent, constructive, contextual, and metaphorical. They consider that knowledge and consciousness are not above experience, but directly grounded in it; the terms used are \textit{embodied} (Johnson, 1987; Lakoff, 1987; see also Talmi, 1988), \textit{enactive} (Varela, Thompson, and Rosch, 1993), and embedded in the \textit{background} (Searle, 1992). There is no separation of mind from body because there is no sense in which the mental is abstracted from the material. All is process, all is emergent. Consciousness, imagination, beliefs, and desires are coequal with reasoning and language, and all are as much part and parcel of human neural activity as is movement or perception.

3.6 EMBODIED COGNITION

One promising path to reconciliation of persistent dualism is through a psychology of embodied cognition. According to Johnson (1987), humans make sense of the world not through abstract, propositional logic (although they can use logic to describe the world) but in a profound and fundamental way, based on real, bodily experience. At the very core of meaning—the way we categorize, remember, talk about, and act in the world—are our experiences as physical beings within a physical world. For example, we encounter \textit{containment} continually in our daily lives. As Johnson (1987) writes:

We are intimately aware of our bodies as three-dimensional containers into which we put certain things (food, water, air) and out of which other things emerge (food and water wastes, air, blood, etc.). From the beginning, we experience constant physical containment in our surroundings (those things that envelope us). We move in and out of rooms, clothes, vehicles, and numerous kinds of bounded spaces. We manipulate objects, placing them in containers (cups, boxes, cans, bags, etc.) In each of these cases there are...
resent an objective, and computer (1987), materialist (1993). These assumptions then lead to the idea that metaphorical structures are a priori. The

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positions views of the digital world—works like digital—and is at core non-constructive, and conscious. As a result, the terms used are

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is through a psychological process (although they fundamentally work)—the way we are our experiences we encounter contain into which other things the beginning, are things (those things be, vehicles, and so placing them in case there are repeatable spatial and temporal organizations. In other words, there are typical schemata for physical containment. (p. 21)

These ideas of containment, Johnson maintains, come to pervade not only our actions but our thought and our language. For instance, he believes that prepositions such as in, out, over, near, under, and so on have meaning only because we have this pervasive, embodied notion of containment—we have experienced it in daily life. The extensions of containment go beyond logic in metaphor and imagery, so that understanding of the term leave out in the sentence, “I don’t want to leave any relevant data out of my argument” (p. 35) goes beyond the physical relationship to a more metaphorical one, based nonetheless on the primal physical understanding.

Embodiment may be at the core of our understanding of literatures as well. For example, Turner (1991) suggests that our recognition of the symmetries in poetic structure and metaphor has its origins in the symmetries and polarities of the body, and that we learn these relationships because we have lived with them in embodied form. “We have a felt, schematic, embodied understanding of bilateral symmetry, and we employ this schematic understanding constantly, moment to moment, in every aspect of our existence, to make sense of our world and to interact with it” (p. 70). The highest levels of human art are part of these interactions.

Along with symmetry and containment, the idea of force embodiment is particularly relevant to my developmental account here (Johnson, 1987; Talmy, 1988). Physical force is something that we deal with at every instance that we move. In order to move through space, we must control our muscle forces. And all our causal relations with our environments require some sort of forceful interaction as we act on objects or they act upon us. Because forceful interactions pervade our daily experience, they also come to infuse meaning. In language, force is the root meaning of verbs expressing compulsion, blockage, counterforce, diversion, enablement, attraction, and so on. Although these verbs may be used in abstract ways, “I am attracted to the ideas of John Dewey,” the meaning is of a forceful pull toward them. Likewise, the common verbs such as could, must, can, might, and so on are understood because our experience has included forceful necessity, overcoming barriers, impulsion, and other acts of force on the environment. Language, in Johnson’s and Talmy’s views, taps into prelinguistic meaning, rather than giving meaning. Experience gives meaning.

3.7 DEVELOPMENTAL DYNAMICS AND EMBODIED COGNITION

Can we move from these philosophical issues of the nature of mind to consideration of the processes and mechanisms by which real people acquire an embodied cognition in their real minds and brains? Here is where I believe that the solution will lie in dynamical conceptualizations, and especially by looking at the origins of cognition from a dynamical perspective. But my

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claim is even stronger: that the developmental data are compelling in support of these new anticomputational views. What is required is to reject both Piaget’s objectivist vision of the end-state of development as looking like a Swiss logician, and the maturationist conviction that there is an executive in the brain or a code in the genes that directs the course of development. Instead, I consider development to be a continuous, contingent, emergent, embedded, nonlinear process that is captured by general principles of dynamical theory.

In particular, I will show in the remainder of the chapter how a dynamical view of development supports force embodiment, a particular aspect of a nonobjectivist cognition. To do this, I begin with a summary of a dynamical systems approach to the development of action and cognition emphasizing the notion of embedded time scales. Next I describe several experimental studies that show that understanding and controlling body forces is a foundational task of infancy. Finally, I offer a more abstract account of how the simple motor tasks of infancy can become embedded in the dynamics of higher cognition.

3.8 A DYNAMICAL SYSTEMS APPROACH TO DEVELOPMENT

A dynamical systems approach to development offers an alternative to both the maturationist and Piagetian accounts I described earlier (readers are referred to the following for extended explications: Smith and Thelen, 1993; Thelen, 1989; Thelen, Kelso, and Fogel, 1987; Thelen and Smith, 1994; Thelen and Ulrich, 1991). A fundamental assumption in a dynamical approach to development is that behavior and cognition, and their changes during ontogeny, are not represented anywhere in the system beforehand either as dedicated structures or symbols in the brain or as codes in the genes. Rather, thought and behavior are "softly assembled" as dynamical patterns of activity that arise as a function of the intended task at hand and an individual’s "intrinsic dynamics" or the preferred states of the system given its current architecture and previous history of activity. Behaving organisms are systems with high dimensionality; they are composed of many, heterogeneous subsystems—neural, physiological, mechanical, and so on—with a nearly infinite number of possible combinations of elements. In dynamical terms, we can see actions and mental life as manifestations of self-organization of these multiple contributing elements. That is, the behavior represents a reduction of the degrees of freedom of the contributing subsystems into a pattern that has form over time. Using my mountain stream example, the flow pattern of the water may be complex, but the pattern is an enormous reduction of the system’s potential complexity arising from the configuration of the stream bottom, the individual water molecules, rate of flow, temperature, wind, and so on, all of which contribute to, but do not program the pattern. Similarly, behavior, although complex, has "sucked in," so to speak, the complexity of the subsystems that support it.
Some of the resulting self-organized patterns of action and thought are very stable because of the intrinsically preferred states of the system and the particular situation at hand. Such patterns of thought and action may be thought of as strong attractors in the behavior space. They attract nearby trajectories, and performance is consistent and not easily perturbed. In the conventional depiction, the potential well is narrow and deep (figure 3.1A). Other patterns are unstable, they are easily perturbed by small changes in the conditions, and performance within the same subject is highly variable and not dependable. Their potential wells are shallow and the system easily shifts between multiple patterns (figure 3.1B). Portions of the space may actually act as repellors, representing coordinative patterns that rarely appear and are highly unstable when they do (figure 3.1C).

Development, then, can be envisioned as a changing landscape of preferred, but not obligatory, behavioral states with varying degrees of stability and instability, rather than as a prescribed series of structurally invariant stages leading to progressive improvement. Although some behavioral preferences are so stable that they take on the qualities of a developmental stage, the stability is a function of the organism-in-context, not a set of prior instructions. In other words, development looks stagelike only because in the immediate assembly of the activity within a context, certain patterns are strongly preferred. Stages are not obligatory prescriptions, rather, they are descriptions of probabilities of certain states.

Developmental change, in turn, can occur only as current preferred patterns are modified by changes in the cooperating elements or the conditions that assemble the pattern of activity. According to general dynamical principles, change cannot occur if the system is rigidly stable—if the attractor is too strong. As system parameters change, however, the coordination of the participating elements may dissolve, resulting in the system searching for a new pattern of stability. Thus, new forms of behavior—the first step or the
first word or the ability to remember the location of the window—can be seen as the product of the confluence of components within a specific problem context rather than the revelation of innate abilities or the inevitable march of determined stages. Dynamical systems shift or bifurcate into new attractors through the destabilization of existing stable forms. Development is likewise a series of both gains and losses as old ways of solving problems are replaced by more functional forms.

This series of evolving and dissolving attractors can be depicted as a landscape of potential wells over time (figure 3.2). In the landscape, time is represented as flowing from back to front. Each horizontal curve represents a state space at a particular point in time: a stability landscape, or the probability that a particular pattern will emerge in a given situation. These are depicted as potential wells, as in figure 3.1. Deep wells represent highly probable behavioral outcomes, while flat portions of the curves indicate the system will hardly ever take on that configuration. As the organism grows, perceives, acts, remembers, and encounters new situations, the old stabilities may be modified or lost completely to new forms as dynamic bifurcations or phase shifts. In addition, the landscape may develop areas of multiple stabilities, representing the more differentiated and adaptive abilities that come with age. These are shown as wide attractors depicting a general category of actions, and containing multiple small basins standing for multiple, task-specific solutions. Note again that the landscape does not prescribe or predetermine a class of behaviors; it is rather a representation of the probabilities of certain actions given particular supporting contexts.

3.9 EMBEDDED TIME SCALES

In this approach, the continuity of time scales is of critical importance. Development, which happens over weeks, months, and years, is part and parcel of the same dynamics as real-time activity, the time scale of seconds and minutes. Mental states and the actions they engender are fluid, flexible, task-specific, and stochastic (not inevitable); they arise only in the confluence of the organism’s intrinsic dynamics and the task. Development has no independent dynamics, but development happens because the organism is continually acting and thinking in the environment, and these activities themselves change the organism. Thus, how individuals solve problems in the real-time scale directly affects the solutions that evolve in ontogenetic time. Development begins with the local dynamics; it is the local dynamics that shape the long-time landscape.

To put this notion somewhat more formally, let us consider the transition from spontaneous movements of limbs to intentional actions, as I describe more concretely below. From birth, and long before infants can sit, crawl, walk, or reach for objects, they are continually waving their arms and kicking their legs. Moving limbs have many springlike characteristics, and indeed, early spontaneous movements in infants may be modeled by a simple,
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Figure 3.2. An ontogenetic landscape: development is depicted as a series of evolving and dissolving attractors. Time moves from back to front. Each horizontal line portrays the probability at any point in time that the system (as indexed by a collective variable) will be in various attractor states. Deep and steep attractors are very stable. Note that the attractor states must flatten out—the system must lose stability—before a new landscape furrow develops. As time progresses the landscape develops multiple stable behavioral attractors. (From Muchisky, M. Gershkoff-Stowe, L. Cole, E., et al., in press.)
damped mass-spring with a regular forcing function (Thelen, Corbetta, Kamm, et al., 1993; Thelen, Kelso, and Fogel, 1987), represented by equation (1).

\[ mx + kx + 5x = F(t) \]  

(1)

where \( x \) is the displacement of the spring and its derivatives, \( m \) is mass, \( k \) is the frictional or damping coefficient, \( 5 \) is stiffness, and \( F(t) \) is the time-dependent energy burst provided by muscle contraction. In this equation of motion describing the ongoing state of the limb system, the coefficients \( m, k, \) and \( 5 \) are all parameters of the system, and \( F(t) \) can also be "parameterized," or take on many values. At any point in time, the mass and the frictional coefficient are constant, as these are determined by the child's anatomy and the elastic and viscous properties of the muscles. However, for each instance of movement, two contributions to the spring can be modulated: the stiffness, determined by the ratio of contraction of agonist and antagonist muscles, and the timing and amplitude of the energy delivered to the limb through the forcing function. In early infancy the settings of these parameters are likely not intentional, but are rather a function of the infant's generalized state of excitement or arousal. That is, excited infants generate more stiff and more vigorous movements, with consequent higher amplitudes and velocities. During normal everyday activities, therefore, infants experience a wide range of spring parameters as they move in and out of a range of energy states, from highly aroused to deep sleep.

Of course, flailing arms and legs are not very useful. In order to achieve intended goals—to put an attractive toy into the mouth or to locomote toward the family pet—infants must adjust their limb spring parameters very specifically to achieve a requisite level of stiffness and they must impart bursts of muscle energy at just the right level and time. They learn to do this, I believe, from experiencing the many different values of the spring parameters generated by their spontaneous movements and movements produced in the presence of a goal. That is, the process involves exploring the range of parameter values in the state space and selecting those values that match the affordances of the environment and the goals of the child. Thus particular spring-parameter values emerge as attractors in the landscape for certain classes of actions, as might be depicted in figure 3.2.\(^1\)

Thus, the first way that the local dynamics evolve into developmental dynamics is through the system continually learning as it acts, each action providing information on the local landscape, and the cumulative effect cascading into the developmental landscape. But there is a second way in which the time scales of action are seamlessly woven with the time scales of development. In equation (1), I characterized mass and damping as constants, which they are over the course of a single activity. Over longer time scales, however, both parameters change dramatically as infants gain weight and as the composition of their limb tissues changes. Most important for our dynamical account is that these changes, too, are a function of the local dynamics. Just as adults can change their body architecture through athletic training,
so too do infants directly modify their structures through movement and weight-bearing. Activity changes the biochemistry and the anatomy of muscles and bones—it makes them larger, stronger, more dense, more efficient, and so on. These changes occur over a more prolonged time scale than do changes in behavior, but they are part and parcel of the same dynamic. Thus, equation (1) both captures a self-organizing system in real time and is embedded in a larger dynamic specifying a relationship between activity and parameters like mass and stiffness.

The spring dynamic may also account for phase shifts or discontinuities, that is, the appearance or disappearance of novel forms. For instance, when newborn infants are held upright, supported under the arms, and with their feet on a table, they typically perform step-like movements. These leg movements may be described by the spring equation. But over the next few months, these stepping movements disappear. In earlier studies, Fisher and I showed that newborn step disappearance was likely a result of the leg mass increasing at a faster rate than muscle strength (Thelen and Fisher, 1983). Babies’ legs get too fat for their muscles to lift up! In terms of equation (1), m is increasing faster than F. The effect would be to decrease the displacement and velocity to a point where the energy cannot overcome the mass, and no movement is possible: a behavioral shift. (This shift has been simulated experimentally by adding progressively heavier weights to infants’ legs; Thelen, Fisher, Ridley-Johnson, et al., 1982.) Conversely, as infants gain relatively more strength than mass in the latter part of the first year, they shift back to being able to lift their legs in the upright position, and even to support their weight.

The point of this example is to illustrate the impossibility of drawing distinctions between the time scales of change. Although change occurs in the fractions of a second of a human action, in the days and weeks of learning, and in the months or years of what we call development, all are embedded in the same, interrelated dynamics. This notion of the continuity and embeddedness of time scales is made especially transparent in the example of limbs as springs with tunable parameters. But I hope to show that the example goes beyond biomechanics in two ways. First, I maintain that the developmental processes by which infants learn to tune their limb springs—exploration and selection—are the same for all behavioral development, including the development of higher cognitive processes. And second, that “limb tuning” itself, as a preeminent activity during infancy, lays a substantive foundation for all mental activities.

3.10 DEVELOPMENTAL ORIGINS OF EMBODIED COGNITION

In section 3.1, I claimed that a major developmental task of infancy was gaining control of the body. This becomes evident to any person who has observed an infant even for a short time. Babies spend much of their waking hours doing things with their bodies—poking, banging, bouncing, crawling.
waving, kicking, crying, babbling. These activities often look playful and sometimes look rather disconnected from any particular intentional goal. I will give some examples of studies of such movements. What the dynamical approach suggests is that, because of the seamless continuities between time scales and levels, these common and indeed unremarkable movements may be laying the foundation of an embodied cognition. As infants explore and learn how to control the forceful interactions of their bodies within their environment, they learn about forces in the specific and local context of those activities. As the force dynamics, in turn, pervade many and varied activities, a more abstracted sense of force emerges and indeed becomes inherent in the dynamics of all mental activity.

3.11 LEARNING ABOUT FORCES IN INFANCY

In this section I present several examples of infants exploring and learning how to control the forceful interactions of their bodies with their environments. The situations are those in which infants have certain desires and goals and need to solve force-environment problems in order to get what they want. In each case, this involves multiple processes—some motivation to do the task, the ability to perceive the task and the layout of the environment, and the ability to control the limbs and body sufficiently to seek a match between their motivation and the particular demands of the task. The examples are young infants learning new skills—in this case how to reach and grasp an object and how to best kick their legs in order to get a overhead mobile to move.

Reaching

We reach and grasp objects so many hundreds of times during the day that it seems to be the most commonplace of acts. Reaching, in reality, requires extraordinary coordination and control. To reach for your morning coffee, you must first translate the three-dimensional position of the cup, transduced through your visual system into a set of coordinates that allow you to move your arm—in a sense converting head-eye coordinates into shoulder-hand coordinates. This is so you can plan on where you want your hand to end up. But that is just the beginning of your problems. Moving your hand is not like controlling a video game with a joystick, where the input is directly related to the output. The anatomy of your arm and the construction of muscles makes the system highly nonlinear—muscles stretch in different ways depending on what you are doing—and it is nearly impossible to get your shoulder and elbow working together to get your hand to do something in a perfectly straight line (try rapidly drawing a long, perfectly straight line on a blackboard). If you move your arm forward rapidly, you need to hold your trunk steady, or it will follow along. Also, a rapid movement creates its own internal perturbations—forces generated at the shoulder

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The neural, mechanical, and computational interface needed for human arm trajectory formation poses a major, and yet unsolved problem engaging engineers, neuroscientists, robotics specialists, and computer scientists. If the control problem has got them stymied at MIT, how in the world does a 2-month old or a 10-month old infant do it? One way might be to build in solutions beforehand. This would be the same as putting the solutions in the hardware design—circuits and chips that have the computations figured out and wait for the baby to turn them on. This leads us to the baby-in-the-head problem. Who designed the chips? Did they get in the head through natural selection, so that people with better reach programs grabbed more food and thus were at a reproductive advantage?

Studying the problem of the origins of reaching from a dynamical systems perspective begins with constructing an attractor landscape, as illustrated in figure 3.2. That is, we want to know, across time, and for a particular situation, which patterns of behavior are stable and when they change. We need to know when systems shift into new forms and when they stay the same. This, in turn, will allow us to discover what parameters actually engender the change. Of the many subsystems that contribute to the final behavior, which are critical in the emergence of a stable reach attractor? To learn this about reaching, my colleagues and I tracked the development of reaching in four infants week by week from the time they were 3 weeks old, barely able to lift even their heads, until they were 1 year old and grabbing things, feeding themselves Cheerios, and playing pat-a-cake. Because, according to our dynamical principles, new forms of behavior must be discovered from the current inherent dynamics, we recorded not just infants' reaching behavior but their ongoing, spontaneous, nonreaching movements as well. Thus, we were able to observe how new forms arose from the dynamics of the existing modes.

The most dramatic transition in reaching were the infants' first successful attempts to touch objects held out for them (Thelen et al., 1993). In our study, two infants reached first at 12 and 15 weeks of age, and the other two, at 20 and 21 weeks. We discovered several important things about this transition to first reaches. First, that infants fashioned reaching from their ongoing movement dynamics. Second, that because individual infants had individually different spontaneous prereaching movements, they had to solve different problems to get the toys they wanted. Third, that all of the infants had to solve problems of adjusting their limb forces to the task. To illustrate this, I contrast in this chapter just two of the four infants, Gabriel and Hannah, before, during, and after their reaching transition. Figure 3.3 is a photograph of Gabriel in the experimental setup.

These two infants had dramatic differences in their overall movement energy. Gabriel was a very active infant. When we placed him in an infant seat, his posture was stiff, his head thrust forward, and he flapped his arms in

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seeming avid anticipation of the toy, almost seeming to fly out of the chair. Gabriel's movements were characterized by wide excursions, high velocities, and repetitive cycling. Hannah, on the other hand, was more of a looker than a doer. She was alert and engaged, and she assessed the situation carefully before moving. Her posture was relaxed, and her movements were smooth and deliberate.

Gabriel's prerreaching movements fit well the model of limb as oscillating spring. Figure 3.4 illustrates Gabriel's spontaneous flapping movements in the week before he reached. I have plotted two examples of the excursions of his hands over the 14 seconds of motion, recording on a phase plane, which plots two dimensions of the movement, displacement and velocity, against each other. Although this is a small sample of behavior, it resembles the periodic dynamical behavior of a limit cycle, depicted as a closed orbit to which nearby trajectories are attracted. In a damped system such as a limb, oscillations are maintained by a periodic infusion of energy, provided in this case by bursts of muscle contraction in Gabriel's shoulder muscles. These phase portraits are
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Figure 3.4 Two examples of Gabriel's spontaneous arm movements when he was 14 weeks old (the week before the onset of reaching) depicted on a phase plane direction in the x-axis (movement from left to right; origin is to the infant's left) vs. velocity. Each hand trajectory is about 14 seconds of movement.
remarkable in their similarity to portraits generated by a forced mass-spring. (Formal characterization of the attractor dimension is not possible because normal infants never produce the long series of movements and thus, the volume of data needed for such analyses.)

In contrast, I have no such recordings of Hannah's spontaneous arm movements. Before she learned to reach, she kept her arms close to her body and made mostly small movements of her hands. In terms of equation (1), she did not provide sufficient force or stiffness to overcome the mass of her arm. Her arms did not enter a limit cycle attractor because the energy parameters were too low.

It should be apparent that in order to make the transition from their preferred spontaneous upper limb movements to limb movements in the service of reaching out and getting a toy, Gabriel and Hannah faced different spring problems. By 3 to 4 months of age, both infants seemed to have a pretty good idea that they wanted the toy and they also seemed to "know" where it was located in space. However, both of their problems were force-related—in Gabriel's case how to get his energetic, off-the-wall movements under control so he could get his hand in the vicinity of the toy. Hannah, in contrast, had to add energy—she needed to stiffen her muscles and extend her arm.

When we observed the actual first-reach dynamics, this is what we saw. Gabriel's first reaches emerged right out of his flaps. He swatted at the toy by going right from the flap to a reaching movement. His movements were stiff, and largely generated from the shoulder. Hannah, in contrast, had slow, well-coordinated movements initiated from a dead stop. She generated low velocities and low forces. Figures 3.5 and 3.6 illustrate these differences by presenting exemplary movements just before and during their very first reaches. In each figure, the top panels show hand pathways as projected onto a two-dimensional plane (like a movie screen in front of the infant). The second set of panels gives the corresponding three-dimensional speeds of the movements, and the third row of panels, the actual calculated torques acting at the shoulder (for details of the model used to calculate torques, see Schneider, Zernicke, Ulrich, et al., 1990; Thelen, Corbetta, Kamm, et al., 1993).

Hannah (see figure 3.5) solved her reaching problem by moving slowly and deliberately, and her resulting movements are rather smooth, direct, and mature-looking. Her hand takes a relatively direct course to the object; she generates low velocities and corresponding low forces at the shoulder. Although Gabriel (see figure 3.6) attempted to slow down his movements as he approached the toy, he still seemed to be captured by his exuberant spring dynamics. Note that his hand pathway has large loops and diversions on the way to the target, and his movements are fast compared with Hannah's. His movements generated high inertial torques and his muscles also produced large forces. The continuity of Gabriel's reach with the spring dynamics of his arms is especially clear when the reaches are viewed in the context of ongoing movements in the phase plane: figure 3.7 gives two examples. The actual
from their predictions in the service of goal-directed movements. She generated these differences by moving slowly, smoothly, directly, and slowly toward the object, and his movements as exuberant spring diversions on the part of the infant. The visuo-tactual feedback, however, did not elicit a goal-oriented response as observed in Hannah’s movements (see Thelen et al., 1993). Figure 3.5 Hannah’s first goal-directed reaches at age 22 weeks. (Top) Hand trajectory projected onto the frontal plane. (Middle) Resultant three-dimensional hand speed during the reach segment. (Bottom) Active and passive torques acting on the shoulder joint during the reach. Positive torques act to extend the joint; negative torques act to flex the joint. NET, sum of all torques rotating the shoulder joint; GRA, torques due to the pull of gravity; MDT, torques rotating the shoulder that result from the movement of other, mechanically linked segments of the arm; MUS, torques rotating the shoulder arising from muscle contraction and tissue deformation. (From Thelen, E., Corbetta, D., Kamm, K., et al., 1993.)
Figure 3.6 Gabriel's first goal-directed reaches at age 15 weeks. (Top) Hand trajectory projected onto the frontal plane. (Middle) Resultant three-dimensional hand speed during the reach segment. (Bottom) Active and passive torques acting on the shoulder joint during the reach. Positive torques act to extend the joint; negative torques act to flex the joint. NET, sum of all torques rotating the shoulder joint; GRA, torques due to the pull of gravity; MDT, torques due to the movement of other, mechanically linked segments of the arm; MUS, torques rotating the shoulder arising from muscle contraction and tissue deformation. From Thelen, E., Corbetta, D., Karmn, K., et al., 1993.)
Figure 3.7 Gabriel's first goal-directed reaches embedded in his spontaneous movements, as depicted on the phase plane. S, start of movement; M, start of reach; T, end of reach; E, end of movement.

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reach itself (the portion of the trajectory between the letters M and T) have the same characteristic dynamics as the spontaneous movements that preceded and followed it.

The infants (and the two others we studied) generated individual solutions to these problems. What we discovered was that the babies could not have had engineers in their genes or their heads with the solutions already figured out. How could a reach program know in advance the energy parameters of the system? The only thing common to the infants’ actions was that they got their hands to the toy and that they manipulated the forces involved to do it. Where did their unique solutions come from?

Time-Scale Dynamics and Developmental Process

Although first reaches are novel acts, the processes that support them must, of course, be continuous in time. That is, something that is going on within the baby in his or her environment prior to reaching must allow the infant to generate the first reach. Some of these processes occur over very long time scales; the changes are slow. For example, body proportions change and muscles get stronger. Vision improves, and infants learn to hold their heads upright.

Other processes are occurring on short time scales. In particular, the integrated acts of perceiving and moving occur within seconds and fractions of seconds. Infants move and perceive many times every day for the 3 or 4 months before they reach. As infants look around, as they suckle, or cry, or as they engage the people around them with smiling and cooing, they necessarily cycle through periods of high excitement and periods of relaxation. What is happening in these everyday encounters? As they move, infants must be exploring what it feels like to deliver different levels of energy to their limbs and also what it looks like to have their hands out in front of their faces or clutching their blankets. This is activity on one particular time scale. Changes occur—dynamics—within seconds or even fractions of a second as infants modulate their muscle contractions in each particular context.

These early movements often look to be entirely without form or meaning. But if what neuroscientists tell us about the plasticity of the brain and how it changes is correct, infants are also continually learning something about their perceptual-motor systems and their relations to the world in their repeated, spontaneous activity (see, e.g., Edelman, 1987; Merzenich, Allard, and Jenkins, 1990). That is, what infants sense and what they feel in their ordinary looking and moving are teaching their brains about their bodies and about their worlds. They are in fact exploring what range of forces delivered to their muscles get their arms in particular places and then learning from their exploration, remembering how certain categories of forces get their hands forward toward something interesting. Thus, the time scale of moving and perceiving becomes part and parcel of the time scale of longer time changes, those of learning itself.

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When this process is put into the metaphor of dynamics, i.e., that the activity of the system itself change the ranges of the parameter values, such an account of development may seem unremarkable. But in many contemporary developmental theories change is ascribed to some deus ex machina — “the genes,” “maturation of the brain,” “a shift into a new stage,” or “an increase of information-processing capacity.” The challenge of a dynamical formulation is to understand how the system can generate its own change, through its own activity, and within its own continuing dynamics, be it the springlike attractors of the limbs or the neural dynamics of the brain. I now report an experimental simulation of a system changing itself through exploration and selection of leg-spring parameters.

Activating a Mobile: Exploration and Selection in a Novel Task

One way to confirm a dynamical view of development is to try to simulate the processes of exploration and discovery in the laboratory. The notion is to create a microgenesis experiment. The term microgenesis comes from the Soviet psychologist L. S. Vygotsky (1978), who recognized that when a developing system was at a point of transition, it could be coaxed into a more mature phase by a facilitative task structure. In dynamical terms, the experimenter is manipulating putative control parameters to shift the system into a new state. The advantage of such experiments is the ability to trace the real-time changes as an analog to those happening during development. It is like a window on the developmental process, but on a more condensed time scale.

In order to do a microgenesis experiment, one must know the state dynamics of the developing system to identify times of transition. Systems that are highly stable resist phase shifts when parameter values are changed.) In the experiment I describe here, the states are described by the patterns of coordination of the legs of young infants as they produce spontaneous kicking movements. In previous work (Thelen, 1985), I described the developmental course of bilateral leg coordination. Before 5 months of age, infants in the supine position kick predominantly in two modes, either both legs alternating or a single leg kicking while the other is relatively still. A third pattern, both legs flexing and extending simultaneously, is much less stable and less commonly seen, until about 5 months, when this pattern becomes more prevalent.

One of the tenets of a dynamical approach is that when the attractor states are relatively unstable, the system is free to explore new coordinative modes in response to task demands. Indeed it is this flexibility to discover new solutions that is the source of novel forms. Thus, I asked, if I presented infants with a novel task that made the initially less stable form of coordination more useful, could they could shift their coordination preferences over the course of the experiment?

Time-Scale Dynamics and the Development of an Embodied Cognition
To do this, I tested 3-month-old infants in a well-known paradigm, that of \textit{conjugate reinforcement} (Rovee-Collier, 1991). In this procedure, infants’ left legs are attached with a ribbon to an overhead mobile. Because their leg kicks are reinforced by the movements and sounds of the attractive mobile, infants learn an increased rate of kicking. To create a task that favored the less stable simultaneous pattern of kicking over the more stable alternating or single-leg form, in some infants I also yoked their ankles together with a soft piece of sewing elastic attached to a foam cuff (Thelen, 1994). The elastic permitted them to kick in single or alternating fashion, but made simultaneous kicking much more effective for vigorous activation of the mobile because full excursions otherwise required stretching the elastic (figure 3.8). Some infants were tested without the tether. I assigned infants to one of four experimental groups, based on whether their legs were yoked together (Y) or free (F) during the three conditions: baseline (4 minutes, no reinforcement, i.e., their leg kicks did not make the mobile jiggles), acquisition (10 minutes, reinforcement; leg kicks activated the mobile), and extinction (2 minutes, no reinforcement; group 1, YF; group 2, FY; group 3, FFF, and group 4, YFF). Would the yoked infants, over the course of the experiment, discover the effectiveness of the simultaneous pattern?

To trace the dynamics of the learning process itself, I tracked the excursions of the infants’ legs during the 16 minutes of the experiment. Figure 3.8 illustrates what these movements look like. The top panel shows a 30-second segment of the excursions of an infant’s leg (the tracked markers were placed on the infants’ shins) as he moved in the direction toward and away from his torso during the baseline condition when his kicks were not reinforced and he right leg minute ing the pat sion pattern. Both left and the right leg were free and the pattern 3.10 (T: correlation exceeded during: the acquisition and YF).
Figure 3.9 Examples from a single infant of leg coordination in the mobile kicking task. (Top) Right and left leg excursions in the z-direction (toward and away from the torso) during the 30 seconds of the baseline condition. (Bottom) Right and left leg excursions in the x-direction during 30 seconds of acquisition.

and he had no ankle tether. This baby kicked in a typical fashion, with the right leg kicking quite a lot, and the left leg only occasionally. After several minutes into the acquisition portion of the experiment, where he was activating the mobile and his legs were yoked together, the same infant’s coordination patterns changed dramatically, as seen in the bottom panel of figure 3.9. Both legs were moving back and forth nearly perfectly in phase.

All the infants, both those whose legs were yoked and those whose legs were free, increased the overall number of kicks when kicking was reinforced, and they also increased the vigor of their kicks. However, the coordination patterns of two groups diverged during the experiment, as shown in figure 3.10 (Thelen, 1994). This figure reports the percentage of values of a running correlation performed on the leg excursion time series that equaled or exceeded \( r = .4.0^2 \). Clearly, the two groups of infants whose legs were yoked during acquisition (YYF and FYF) increased their simultaneous kicking during the acquisition period (A1–A5), whereas those in the free condition (FFF and YFF) decreased their inphase movements. During the extinction phase

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Figure 3.10  Percent of right and left leg excursions correlated at $r=.4$ and above in the four experimental groups. Y. yoked; F, free. Trial blocks are 2 minutes except for extinction when they are 1 minute.

(E1 and E2) when kicks were no longer reinforced and the tether was removed, the yoked infants dramatically resumed the originally favored patterns.

This experiment demonstrated that within the time scale of a few minutes, infants as young as 3 months can shift patterns in response to a novel task. Infants clearly enjoyed making the mobile jiggle with their leg kicks, and they also learned to do this efficiently "on-line." When the task constraint was removed during extinction, there was no longer any need to maintain the novel pattern and they did not.

In dynamical terms, we can envision each leg as having adjustable spring parameters and also there being a modifiable coupling function between the legs. The experiment can be interpreted, therefore, as infants discovering an optimal coupling pattern as well as adjusting the timing and the strength of the energy bursts to the spring, delivering more frequent and stronger pulses. In terms of the dynamical landscape of figure 3.2, the babies have created a new potential well, a newly attractive parameter configuration emerging from their on-line solution to getting the mobile to jiggle in an efficient way.

3.12 FROM ACTION TO COGNITION

Reaching and kicking a mobile are both about learning to adjust limb force dynamics. These studies showed first, that infants generate individual solutions to adjust body forces to do a task and second, that they can select appropriate patterns of coordination from among several within the time scale of acting and learning. What does this mean in terms of changes over longer time that these cognition?

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longer time scales—development—and, particularly, in terms of my claim that these mundane infant activities support the construct of an embodied cognition.

The critical process here appears to be that of learning categories, in this case, that a certain category of force dynamics is appropriate for a certain class of tasks. As Thelen and Smith (1994) discuss at length, perceptual motor category formation is foundational for all cognitive development (see also Edelman, 1987, among others). The ability to recognize that particular perceptual events and actions generalize is what lays the groundwork for being able to make sense of the world. For instance, by watching objects move in space, infants learn that edges that move together define the boundaries of objects, and they come to expect that even novel objects—things they have not seen before—will act as a coherent whole. Likewise, they learn that small, colorful objects 6 in. in front of their bodies mean something that may feel good in the mouth and they acquire and remember a class of muscle parameters for reaching and grasping for all suitable objects in reachable space. Thelen and Smith (1994) use developmental evidence to show the dynamical nature of categories. In particular, that category formation may also be depicted as a landscape of potential wells, where the local acts of perceiving and acting come to form wider basins of attraction that represent more general classes of solutions.

The mobile experiments provide insights into how the process of forming higher-level categories from local activities may proceed. Recall that when I tethered infants’ legs with elastic, they discovered a force solution, but when the tether was removed, they reverted to different patterns. The appearance and disappearance of the tether is in some ways like what infants encounter in everyday life. Tasks and constraints appear and disappear. Opportunities for action depend on the presence of desired objects, suitable support surfaces, helping social support, and so on. In one way, every particular opportunity is unique—toys are never in the same location or orientation in relation to the infant. But infants commonly encounter similar classes of opportunities, for example, the category “toys able to be reached.”

So an important developmental question remains: How do infants generalize from each unique opportunity to act—the here-and-now dynamics—to novel, but similar situations? Then, how do the accumulated classes of solutions themselves influence what we call the qualities of mind?

There are very few experimental studies that span the here-and-now dynamics and the dynamics of developmental time. Some of the most enlightening, in my opinion, use the mobile kicking situation and have been done by Carolyn Rovee-Collier and her colleagues (reviewed in Rovee-Collier, 1991). What Rovee-Collier asked was, once infants learned to kick more in the presence of the mobile, did they remember to do so days or even weeks later, and then, under what conditions do they remember or forget how to match their actions to the task?

Rovee-Collier found that 2- to 3-month-old infants could remember, and if given the mobile the next day or even a week or two later, resumed kicking.
at the high rate they learned in the original session. (My preliminary evidence is that infants also remember the new pattern of coordination elicited by leg tethering.) Over time, this memory faded, although simply seeing the mobile would reactivate it. Most important is that this action memory was highly specific to the training situation. If Rovee-Collier changed the mobile, or even the designs on the pads that lined the cribs in which infants originally learned the task, infants forgot that kicking a lot makes the mobile move more. The action memory was highly tied to the learning context. However, if Rovee-Collier trained infants on the first day with one mobile or set of crib liners, on the second day with a different set, and on the third day with yet another set, the infants did remember to kick no matter what mobile they were tested with—even a completely novel mobile. Whereas the first learning was highly specific, infants, given different mobiles, generalized from a particular situation to a category of mobiles-to-be-activated-by-kicking. Thus, they tied their bodily actions to a perceptual category such that the sight of the mobile and the learned motor response were united. The common attractor is now “mobileness” in general—depicted in a figure 3.2-type landscape as a broad attractor with several embedded potential wells.

The mobile studies created, of course, highly artificial situations for infants. In normal life, they bang and reach and look and grasp not just one thing, but many different things—toys of many kinds, textures, and weights; people, pets, and in many different places; their crib, the grass, their blanket, and so on. So real life gives abundant opportunity to learn by doing, to discover, and to generalize—that yes, a certain force delivered to my arm will get me any object of a certain size and at a certain distance, but to pull up a Cheerio, I may have to slow down and adjust my fingers. It is indeed this diversity, this variability of experience, that allows more general solutions to emerge.

In both of the examples above, infants solved problems of how to control the forces generated by their limbs and bodies in order to make the world work for them. In each case, the infants must eventually not just meet the situation at hand, but recall and use a category of action solutions that fits what they perceive their task to be. If you think about the developmental tasks of infancy, however, you quickly realize that this cycle of challenge, exploration, discovery, and new challenge within the motor skill domain occupies a large part of the child’s waking hours. Although each task is unique, the solutions must be generalized. As each new solution is discovered, that solution opens up new opportunities to learn. It is through these successive generalizations that cognition grows from action and perception (Thelen and Smith, 1994).

3.13 TOWARD A FORCE EMBODIMENT

Indeed, I speculate here (following Johnson, 1987; Lakoff, 1987; Langacker, 1986; Talmy, 1988) that the solutions to force interactions with the world are so pervasive and foundational in infancy and indeed throughout life, that
Figure 3.1: Face embodiment pictured at first stage and then overlapping choice.

Figure 3.2: Face embodiment pictured at second stage.

Figure 3.3: Face embodiment pictured at third stage and then overlapping choice.

Figure 3.4: Face embodiment pictured at fourth stage.
continue to dominate everyday life. The notion is that we have lived in these
intersections so thoroughly that they are embedded and embodied.

Of course, forceful encounters between body and environment are only
one way in which we interact with our worlds. Social communication rarely
involves direct force, but provides rich information to many of our senses.
And social encounters are equally pervasive. We can think of the develop-
ment of social life also as a series of challenges. The tasks are to figure out
what Mom wants and to get her to figure out what you want. Many avenues
are explored ("Perhaps lying down, screaming, and kicking my feet will work").
Some are functional, others are not. Over time, however, increasingly gen-
eral, individualized solutions that involve facial expressions, vocalizations,
gestures, postures, and of course language, are selected. As in body actions,
the solutions to communication will have many intersections in mental state
space. We may thus speculate that our cognition, our very way of thinking,
would be equally influenced by the root metaphors of our social exchange
and, in particular, by the patterns of social life peculiar to our families and
cultures. This has long been the claim of psychologists such as Vygotsky and
Luria, and lately Jerome Bruner, that patterns of thought reflect the very
societies in which they developed. Perhaps an account such as I have sug-
gested can give "embodiment" to these ideas as well.

NOTES

1. It is important here to clarify the role of goals and intentions. To say that infants are
motivated to perform and repeat certain activities, like looking at moving objects or reaching
for toys, does not require putting an agent back into the baby's head. What is required is that
the system come with a few, very general biases, e.g., looking at moving things is better than
not looking, having something in the mouth feels good, and so on. With just a minimum of
biasing tendencies, the developmental system self-organizes in relation to those tendencies,
and indeed produces an additional motivational cascade. For example, the biases "look at mov-
ing things and get things in the mouth" are sufficient to provide the motivational basis for reaching,
grasping, and exploring. This is not the same as having a little executive in the head program-
morphing behavior and its changes. Even the most simple organisms have tropic biases: toward
moderate amounts of heat, light, moisture, and so on. Thelen and Smith (1994) discuss further
the relation of simple biases and motivation, including its neurophysiological basis.

2. Quantifying patterns of coordination over time is difficult in infants because the phase
relations are always changing. To capture these shifting relations, I performed a moving win-
dow correlation of the 1-displacements of both legs using a 1-second window and a step of
17 ms. I could then determine the frequency bins of each correlation value. Correlations near
+1 indicated both legs moving toward and away from the body exactly in phase, correlations
near -1 resulted from alternating movements, and correlations around 0 meant the move-
ments were unrelated. (See Corbetta and Thelen, 1993, for details.)

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Guide to Further Reading
Thelen and Smith (1994) contains a full version of a dynamical theory of development, beginning with general principles and then showing how cognition emerges from perception and action. The chapters in Smith and Thelen (1993) give applications of dynamical approaches to the development of movement, perception, infant state, cognition, language, and social interaction. Thelen and Ulrich (1991) is the first developmental study undertaken from a specifically dynamical point of view. A compatible, synthetic view of neuroembryology and brain function can be found in Edelman (1987). The August 1993 issue of the journal Child Development (Vol. 64) contains a special section entitled "Developmental Biodynamics: Brain, Body, Behavior Connections," which has many papers relevant to the origins of an embodied cognition. Finally, Savelbergh (1993) contains a number of papers studying infant development from a dynamical viewpoint, but also provides contrasting perspectives.