U-Shaped Changes in Behavior: A Dynamic Systems Perspective

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The traditional view of development is stage-like progress toward increasing complexity of form. However, the literature cites many examples in which children do worse before they do better. A major challenge for developmental theory, therefore, is to explain both global progress and apparent regression. In this article, we situate U-shaped development as a special case of the nonlinearity that is characteristic of all developmental process. We use dynamic systems theory to show how behavioral regression can be understood as part of the ordinary mechanisms of change. Examples from our work in infant motor and language development illustrate the ways that U-shaped behavior arises from continuous changes in the collective dynamics of multiple, contingent processes. A central claim is that true regression is not possible because behavior exists continuously in time. Thus the current state of the system always depends on its past history. Instead, the appearance of regression reflects the concept of softly assembled behavior, or the ability of contributing components to self-organize in different configurations that depend upon the status of the components, the environment, and the task.

The classic definition and logic of development is the inevitable progress from child to adult (Ausubel, 1958; Werner & Kaplan, 1963). Over several generations of research, developmentalists have carefully catalogued these changes, revealing a steady and increasingly complex progression from one ontogenetic level to the next. Based on these rich empirical descriptions, we know much about the sequence and timing of states through which individuals pass—how infants think and perceive,

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how they control their movements and learn to speak, and how these global descriptions correlate with age. Although there is obvious continuity across these levels, much of development has been portrayed as a series of stages that are qualitatively distinct, structurally discontinuous, and relatively abrupt. Everyday observation is consistent with this view: babies crawl before they walk, babble before they speak their first words, and reason on the basis of appearance before they reason on the basis of reality. Each stage is a stepping-stone to more complex and adult-like behavior.

Given these common and traditional assumptions about development, researchers have been both puzzled and intrigued when they discover their assumptions are violated in the form of regressions, or losses of previously performed behavior. These phenomena, which have been described in many domains and for different ages of children, have been called “U-shaped” development (Bever, 1982; Strauss, 1982). A classic example occurs in language development between about 2 and 3 years of age: children sometimes use words like “foots” and “goed” after several months of correct usage. Following this brief period of overregularization, they eventually resume the correct form. The questions remain: how can a child seemingly have an ability and then lose it, only to have it reappear later in the developmental sequence? What does this mean about stages as stepping-stones to more mature forms? How can a continuous process lead to such dramatic discontinuities?

In this article, we show how dynamic systems theory can help explain both the global, often stage-like progress of change toward more complex forms, and its occasional, apparent regressions, where progress seems to stop or even go backward! We situate U-shaped development as a special case of the nonlinearity that is characteristic of all developmental processes. We argue that such nonlinearities are the inevitable product of complex systems, composed of many, often heterogeneous parts that can assemble in different configurations, depending on the status of the components, the environment, and the task.

We begin this article with a brief consideration of the way regression has been generally conceptualized in the literature and contrast that view to dynamic systems theory. Next we present a summary of the basic principles of dynamic systems theory and its significance to understanding developmental change. Finally, we use examples from our work in infant motor and language development to show how these concepts can be used to uncover the underlying mechanisms of change. In particular, we show that regressive or U-shaped development can be understood as part of these normal mechanisms of change.

**CONTRASTING VIEWS OF U-SHAPED DEVELOPMENT**

**Explaining Progress as Well as Regress**

Developmental change has been generally studied from the vantage point of low levels of magnification. Thus developmentalists have been concerned with qualitative similarities and differences between younger and older children. For example, do
children search for a hidden object in a classic Piagetian task? Global order questions such as this are often guided by theories that cast development in terms of existing mental structures: If children do search, then they have the structure of object permanence. Development, then, proceeds by moving from one static structure to the next. Once the child acquires the structure, it is the structure that organizes subsequent behavior.

One problem with this view is that global accounts of development are thus set apart from children’s real-time activities. Indeed, careful study of the moment-to-moment flow of real behavior reveals considerable variability from one act to another rather than evidence of some overarching structure. For example, in tasks where children must solve simple arithmetic problems, researchers commonly believed that children first settle on using one strategy, and with much experience solving addition problems, then move onto another strategy (Groen & Parkman, 1972). For instance, children might first use their fingers as an aid to counting, then count out loud without external support, and finally internalize the process so that rapid retrieval is possible without visual or audible support. More recently, however, Siegler (1987; Siegler & Jenkins, 1989) conducted trial-by-trial analyses of children’s strategy choices and found that rather than relying on only a single approach at a time, children use multiple approaches for solving problems. Moreover, children do not simply substitute one strategy for another in hierarchical fashion. Instead, what changes with development is the frequency of use of each strategy and the range of situations to which children apply them.

Variability of this kind is pervasive in development when we look for it (Thelen & Smith, 1994). Variability is not merely “noise” in the system. Nor does variability reflect the vagaries of performance factors that interfere with the expression of the global mental structure. Rather these temporary gains, losses, and hesitations that mark the path towards mature growth offer important clues to the study of change, and indeed may be the very source of change. Yet this variability poses a real challenge to theories that attempt to explain the nature of transition between global order structures (see also Fischer, 1983, for a related view).

Behavior at the global and local level offers two different realities. At the global level, developmental transitions are like objects in classical physics: qualitatively distinct and bounded entities. At the local level, transitions are like “objects” in particle physics: complex processes that happen in real-time. Importantly in a theory of change, the mechanism that controls both growth and decline can only be understood in the close-up detailed study of real-time processes. In contrast to many other contemporary theories, dynamic systems theory offers such a model of transformation—one that integrates global order change with individual acts of behavior.

Characterizing the Nature of the Relation Between Behaviors

Regressions in development refer to temporary slides or dips in performance that often accompany periods of rapid transition. A fundamental question is how best
to describe the character of the relation between earlier and later behavior. Ausubel (1958) stated that in regression, "the individual reverts to an earlier and more primitive level of growth characteristic of younger or less mature individuals" (p. 106). Other researchers speak similarly of regression as the loss, disappearance, unlearning, or abandonment of behavior (Bever, 1982; Strauss, 1982). Recently, however, some theorists have suggested that regression is better viewed as a marker of improvement rather than decline. For example, Stager and Werker (1997) emphasized that changes in the ability to discriminate between native and nonnative contrasts in language is a matter of reorganization rather than loss. That is, although performance may deteriorate locally, there are long-term, global changes that indicate overall positive growth.

What, then, is the relation between the initial behavior in a U-shaped function and its subsequent appearance in a more "mature" form? Klahr (1982), for example, discounted the importance of the relations altogether. He argued that such U-shaped patterns are merely artifactual—imposed by experimental methods that constrain how performance is measured. In other words, U-shaped curves mask what is actually continuous monotonic improvement. Consistent with this idea, Karmiloff-Smith (1992) proposed a distinction between behavioral change, which sometimes gives the appearance of U-shaped growth, and representational change, which progressively improves. Karmiloff-Smith argued that change at the representational level reveals true differences in the child's state of knowledge. By her account, the relation between earlier and later behavior is one of "representational redescription." That is, sensori-motor routines are subsequently recoded into an abstract and more flexible form. As such, the representations of older children are manifestations of different and "better" conceptual processes than those of younger children, even when their surface properties are similar.

Other explanations of regression focus on the actual replacement of one representational system for another. Often these new ways of representing the world present a conflict for the child and may act as the underlying mechanism of change (Goldin-Meadow, Alibali, & Church, 1993). For example, Strauss (1982) reported a pattern of U-shaped development in children's conceptual understanding of temperature. Young children know by common sense that water remains cold when more cold water is added. He found that between 6 and 9 years of age, however, children's early commonsense notions clash with their emerging awareness of additivity (e.g., 10 buttons + 10 buttons = 20 buttons, but 10 °C + 10 °C ≠ 20 °C). Consequently, in tasks that require children to compare the temperature of one cup in which equal amounts of 10 °C water is added to that of a second cup of 10 °C water, older and younger children tend to solve the problem correctly (although for different reasons), but most 6- to 9-year-olds do not.

These findings and others (e.g., Bever, 1982; Bowerman, 1982) have generated much debate over how best to characterize the nature of the replacement from one knowledge state to the next. Are such changes a consequence of increasing differ-
entiation or integration (Strauss & Stavy, 1982)? Does one system override or eventually suppress the other? Such questions are of interest not only to students of conceptual development, but also are relevant in other domains. In the area of perceptual development, for instance, Johnson, Dziurawiec, Ellis, and Morton (1991) observed that at birth and 2 months of age, infants demonstrate preferential responding to face-like patterns over nonface-like patterns. However, at 1 month, infants show a decline in the rate of preferential responding. Johnson et al. proposed two independent mechanisms, Conspec and Conlem, to account for these U-shaped changes. They suggested that the change in infants’ attention to faces was due to a critical shift, between 4 and 6 weeks of age, from subcortical to cortical mediated control. One consequence of this important neurological event is the suppression of Conspec—a mechanism available from birth—by the developmentally mature mechanism, Conlem.

The current debate about developmental regressions stems, in part, from two aspects of Piaget’s legacy. On the one hand, many have invoked Piaget’s stage theory, with its emphasis on qualitative shifts from one structural level to another. From this global perspective alone, it is difficult to understand regressions. On the other hand, Piaget also sought to explain developmental change by reference to the ontogenetic history of the individual. Here his concern was with the continuous relation between multiple variables at different points in time. Past experience perceiving and acting on objects in the world thus provides a basis for understanding future behavior.

PRINCIPLES OF DYNAMIC SYSTEMS THEORY

Dynamic systems theory offers a comprehensive framework for studying transition that we believe captures the true complexity and variability of development (Thelen & Smith, 1994; Thelen & Ulrich, 1991). Moreover, it is a theory that is broadly applicable to diverse areas of inquiry. We highlight here two central assumptions of dynamic systems theory that are key to our understanding of U-shaped behavior. The first, continuity, is common to some other theories of development. The second, soft assembly, is unique to a dynamic approach.

Continuous in Time

We believe, with Piaget, that apparent discontinuities arise from processes that are continuous in time. Thus, the first important tenet of dynamic systems theory is that the long-term and recent history of the system affects its current state. According to the dynamic view, the developing system is, by definition, always changing. Behavior exists in time such that states of the system in the past contribute to its present state and future states. Oyama, Griffiths, and Gray (2001) have character-
ized development as continuous "cycles of contingency." This means that every current state is contingent on what went before. For this reason, a true regression to a former state is impossible. What has evolved cannot be undone; a later state cannot be dissolved into a former one.

Thus, people with brain lesions may show child-like behavior, but the similarities of behavior arise from very different underlying mechanisms (Thomas & Karmiloff-Smith, 2002). For instance, both newly walking infants and adults with Parkinson's disease walk with a shuffling gait, taking short steps and placing the whole foot on the ground, rather than rolling forward from the heel to the toe. Forssberg, Johnels, and Steg (1984) suggested that Parkinson's patients have lesions in the same part of the brain that has not yet matured in new walkers, that is, both have shuffling gait from the same brain insufficiency. But shuffling gait is a solution to a more general problem, lack of balance. When either a Parkinson's patient or a baby cannot balance well on the stance leg, they find a common solution: take short steps to spend less time in single leg stance. By the same reasoning, abilities that disappear in development cannot reappear unchanged by the ongoing developmental events. Thus, the question about U-shaped development must be reformulated. The issue is not how a behavior is "lost" or "gets worse," but how the component processes can reorganize to produce such dramatic nonlinearities in performance.

Soft Assembly

Biological dynamic systems, like dynamic physical systems, are composed of multiple, heterogeneous elements. Under specific conditions, such systems self-organize to produce complex patterns that change over time (Kelso, 1995). Self-organization means that the organized patterns arise strictly from the interaction of the constituent parts. The hallmark of dynamic systems is a kind of circular causality, where no component part has causal priority over the others; the behavior of the system depends on all the constituents, including those in the physical world in which the system is embedded. Thus, development is the product of multiple and co-dependent elements or subsystems cooperating within a single system (Oyama, 1985). New developmental patterns arise in a self-organizing fashion as a function of the changing interrelations between internal processes and contextual influences.

In this sense, behavior is "softly assembled"—many different configurations are possible from the constituent parts, although some are more stable or "attractive" than others. Behavioral stability arises as a function of both the child's history and the current context. Thus, some behavior is very stable and resilient to changes in the task, whereas other configurations are unstable and easily perturbed. This notion of stability explains the persistent and puzzling decalage so common in developmental studies: why children sometimes appear more or less proficient when
the current context and task demands change. For example, although 10-month-old infants are able to search successfully for a hidden object, this ability is fragile and depends on many local factors, including the delay between hiding and searching, the number of A trials, the distinctiveness of locations, and the number of practice trials involving reaches toward a goal (Bremner, 1985; Harris, 1987; Marcovitch & Zelazo, 1999; Marcovitch, Zelazo, & Schmuckler, 2002; Smith, Thelen, Titzer, & McLin, 1999).

Because dynamic systems are nonlinear, some components may have a strong influence on the final assembly and dominate others, depending on the status of that component in that situation at that time. That is, at times the system may be particularly sensitive to changes in one or more of its parameters, such that a small change in this component can shift the system into new forms. But we cannot say that this one element causes a developmental change because the influence of this element is only within the particular constellation of all the other contributing elements at a particular time. It is not a static or permanent arrangement. Each component of the final behavior is itself changing on some time scale, ranging from seconds to days, months, or years. When the component changes are slow and the context is stable, then the softly assembled behavior may appear stable. Conversely, when the components themselves are in rapid flux, there may be changes in the relative contributions to the ensemble and thus, the behavior itself may be fragile and transient. By this logic, U-shaped behavior is the result of these continually changing configurations that may give the appearance of regressions, but are actually windows on these processes of continual reorganization in systems undergoing relatively rapid change.

In summary, new behavior can emerge in development for reasons that may be neither directly nor obviously related to events that are prior. All biological systems produce coherent behavior from ensembles of multiple parts that are themselves continuous in time. This is as true for a behavior as complex as human language as it is for locomotion in simple animals. The challenge is to account for both the changes that are incremental and linear, as well as those that are stage-like and nonlinear, including seemingly regressive changes.

**U-SHAPED BEHAVIOR AND INFANT STEPPING**

A well-known but nonetheless transparent example of U-shaped behavioral change is the regression of the newborn stepping motor pattern that occurs in normal infants around 3 months of age and its reappearance at about 8 months. When newborn infants are held upright, with their feet on a surface, they make step-like movements, with often alternating leg flexions and extensions. After a few months, these movements become increasingly difficult to elicit under normal circumstances. Not until later in the 1st year do infants resume stepping, prior to cruising
and walking. The traditional, single-cause explanation is that newborn stepping is a primitive, subcortical reflex that is inhibited by maturing higher centers in the brain, and that “real” stepping reappears when those brain centers are sufficiently developed to produce voluntary movement. According to this explanation, maturational changes in the brain account fully for the U-shaped path of developmental change (Forssberg, 1985; McGraw, 1945).

The infant brain does change rapidly during these early months, but brain changes alone are not responsible for these U-shaped changes. Rather, whether infants step or do not step is a function of a dynamic confluence of factors, including the infants’ own bodily changes, their individual movement histories, and the particular context in which stepping is elicited.

First, consider a source of change unrelated to maturation of the brain. Thelen and her colleagues (Thelen & Fisher, 1982; Thelen, Fisher, & Ridley-Johnson, 1984) discovered that while newborn stepping movements, always elicited by holding the infant upright and on a surface, did indeed decline, newborn “kicking” movements, done in supine, did not, and indeed became more frequent. Moreover, at the kinematic level as well as at the neuromuscular level, stepping and kicking looked very much alike. That is, the joint rotation patterns and the patterns of muscle activation were identical in the two types of behavior. The only things that differed were the infants’ positions. It seemed unlikely that cortical maturation would affect movement in one position, but not another.

While the brain and nervous system are always involved, movements are also always performed within a particular biomechanical context. This may include the nature of the supporting surface, but also the mass and inertial properties of the moving limbs. Thelen and Fisher (1982) found that these biomechanical considerations made it more difficult for infants to lift their legs when they were upright than when they were supine, where gravity assists in bringing the knees back. Most importantly, in the 1st months of life, the biomechanical properties of infants’ legs change very rapidly because they gain considerable weight, primarily as subcutaneous fat. This means that while the legs get heavier, they do not increase muscle mass in proportion. Infants can overcome this increased leg mass while supine, but not in the more demanding upright position: they stop stepping, but kicking continues. Later, as muscle mass and strength increase, infants overcome these biomechanical restrictions and again, step when upright. If this explanation is correct, then manipulations that decrease the biomechanical demands on the legs should produce stepping during the time when infants normally do not step. Indeed, Thelen, Fisher, and Ridley-Johnson (1984) restored stepping in nonstepping infants by submerging their legs in water, effectively lessening the biomechanical load on the muscles.

These non-neural changes may be one reason that Zelazo, Zelazo, and Kolb (1972) were able to maintain stepping through repeated training. Young infants given daily “practice” stepping continued and even increased their steps while control infants decreased their steps. One consequence of this training in the de-
manding upright position may have been to improve the strength of infants’ legs, enabling them to overcome their added nonmuscle leg mass.

But the training provided by Zelazo et al. (1972), in their classic experiment, may also have provided enriched input to the neural pathways subserving these movements. As with adults, training can impact both muscle strength and skill itself. Thus, the intervention may have multiple effects in a complex, situation system.

This example of U-shaped change is informative for two reasons. First, the parameters influencing the behavioral changes themselves changed during development. The processes underlying the performance of the behavior were very different at different ages. Second, at least some of the parameters were not specific to stepping. In no sense is weight gain directly related to stepping. Babies need to have subcutaneous fat for temperature regulation. Likewise, infants gain muscle mass and strength in all parts of their bodies, so this change is also nonspecific. Stepping or no stepping is the emergent product of these rapid changes in body mass, and composition and patterns of use. No stepping “program” or dedicated locomotor module controls these changes. Although stepping appears, disappears, and reappears, these changes reflect organismic reorganization, which happen to produce similar surface behavior.

**U-SHAPEd BEHAVIOR AND INFANT PERSEVERATION: TWO EXAMPLES**

Similarly, regressions and reappearances seem surprising when cognitive development is viewed as single-causal and “disembodied,” that is, isolated from the more general perceptual and motor processes that accompany every behavioral act. In the stepping example we just offered, the U-shaped development is better understood when the system as a whole is considered, not just a dedicated part of the brain or a single type of experience. Here we offer two additional examples where infants appear to get worse before they get better, but also where similar surface behaviors are the result of system-wide reorganization. Importantly, in these examples, U-shaped performance was predicted theoretically from a dynamic systems model, and subsequently confirmed by experiments. The first example concerns infant reaching in Piaget’s classic A-not-B task. The second example addresses recent findings on the development of word retrieval processes in a simple picture book naming task.

**Perseverative Reaching in the A-not-B Task**

Piaget’s “A-not-B” error is one of the most widely studied behaviors in the infant literature. As is well known, the error arises when 8- to 10-month-old infants are cued to recover a hidden object from one of two identical hiding places. After sev-
eral recoveries at the first "A" location, the experimenter switches the hiding place to the second "B" location. The infant watches the toy hidden at the new location, but, if there is a delay between hiding and allowing the child to reach, infants robustly perseverate, that is, return to the original "A" location. Infants older than 12 months, however, are able to track the toy displacement with the short delay.

The source and meaning of A-not-B behavior has been the subject of intense theorizing and experimentation because of Piaget's original descriptions and interpretations. The debate revolves around whether the A-not-B task is about the "object concept" as Piaget and others have suggested (e.g., Butterworth, 1977; Piaget, 1954), or whether it indexes changes in other aspects of infants' behavior such as their spatial abilities, short-term memory, or cortical executive functioning (e.g., Acredolo, 1985; Diamond, 1985). The task remains intriguing because, while robust in some forms, it is also exquisitely context-sensitive, so it is amenable to many different experimental treatments. Notably, no single-cause theory has been able to explain not only the canonical experiment, but also its many context-dependent variations.

Recently, Thelen, Smith, and colleagues (Smith et al., 1999; Thelen et al., 2001; Thelen & Smith, 1994) proposed a dynamic field model that accomplished this purpose. The new theoretical stance was inspired by the tenets of a dynamic systems approach, and in particular, that behavior was emergent from many contributing elements and evolves over time. These ideas, in turn, led to several new experiments (Diedrich et al., 2000; Smith et al., 1999). The key experimental finding was that infants perseverated just as readily with no hidden object at all, but simply in response to the experimenter's waving the lid to the hiding places. An important second finding was that perseveration was dependent on the number of trials to the A side, suggesting the build-up of a habit (see also Marcovitch & Zelazo, 1999; Marcovitch, Zelazo, & Schmuckler, 2002).

These experimental results supported the idea that A-not-B behavior is not only about mental representations of objects and their properties, but also about reaching for things, and the perceptual and cognitive processes that lead to a decision to move. These included the visual properties of the targets and the cues to reach to one side or the other, the persistence of the visual input when it was no longer available, the time-dependent processes that integrate the inputs and result in a decision to move, and the memory build-up of repeated reaches to one side. These processes all contribute in an integrative, but nonlinear way. Most important, these processes are not specific to infants, but are more general processes involved in moving adaptively in the world.

Thus, perseveration arises at a particular developmental moment because of the normal evolution of voluntary behavior and the mechanisms that underlie it. These include the abilities to perceptually identify the target, which may be confusing or only partially visible; to remember the target object and location when it is no longer visible; to decide between conflicting stimuli; and to remember the results of previous actions to use to plan subsequent ones. Perseveration occurs at any partic-
ular developmental age, in this view, because remembered aspects of the previous behavior conflict with the new stimuli. Because this behavior is "softly-assembled," it is both a product of the developmental status of the actor, but also of the situation that elicits it.

We show how such a conceptualization predicted U-shaped behavior, which was verified experimentally. We later illustrate how the model explains perseverative behavior in older children as well, and in different tasks. We begin by discussing the formal model and simulations that led to the U-shaped prediction.

The Model Begins With a Task Analysis

A multi-causal and time-dependent explanation of infant perseveration is captured in a formal mathematical theory using principles of dynamic field modeling (Thelen et al., 2001). The model requires a particularly careful analysis of the task.

The theory conceptualizes the A-not-B error as arising from the confluence of the ordinary processes of looking, deciding, reaching, and remembering. First, infants look at the task layout. In the typical case, the task consists of two identical target places, usually cloths or lids to hiding wells, placed 6 to 8 in. apart. This task layout provides a more-or-less continuous input to the baby indicating the two choices, reach to A or reach to B. The experimenter then provides additional visual and auditory cues to the child as to the desirability of the toy and to the place where it will be hidden. This is a transient cue that the infant sees for only a few seconds. Then the experimenter sometimes imposes a delay. Because there is a delay between a cue to act and the action itself, the cue must be remembered. In the time between the cue and the action itself, the infant must make an action decision to reach to A or to B. This decision is a function of the strength of the cue—how interesting or intense—and also of the baby's past history, because the child comes into this situation with a set of expectations built from past experiences. Thus, for the A-not-B task, as for any action, the decision is the condensation of multiple factors that have influence over multiple time scales.

Equally important is that once the action decision is executed—the baby reaches to A or to B—that action is remembered and, in turn, influences subsequent decisions. Thus, as in everyday life, the infants' actions cascade to form a rich and complex internal context that includes not only the consequences of the action but also its execution in movement and perception.

By this account, then, infants produce the A-not-B error because they face a task context that is somewhat novel and confusing to them: two identical targets. They are enticed to choose one target to reach to by the experimenter's attention-getting activities at that target. This pulls their decision to the A side and they set the appropriate muscle synergies in motion. Once they have reached once to A, however, the memory of the A reach lingers long enough to exert influence on the next decision. One reach to the A side gives a slight bias to the A decision. As the experimenter continually cues the A side, however, this memory bias grows. After
a number of A side reaches, the target is switched. Now the infant gets a transient
cue to the B side. The memory of the B cue fades but the memory of the A reaches
does not. Over a short delay, therefore, the A memory competes with the B cue and
it wins out. Infants reach back to A. This mechanism is illustrated in Figure 1.

In particular, the structure of a typical A-not-B task involves repetition, as in-
fants are always cued more than once to the A side. This repetition is critical be-
cause it is the memory of the A reaches that sets up the conditions for
perseveration. Specifically, repeated reaching to the A side creates a kind of habit.
Each reach to A is remembered and that memory biases the next action of the in-
fant. A straightforward prediction of this assumption is that the more reaches to the
A target, the more likely infants would perseverate when tested at the B target. Smith et al. (1999) tested this prediction directly. Infants who reached one or three
times to A did not reliably persevere, while infants who reached five times did. In
other experiments, they also showed that individual infants who consistently

**FIGURE 1** A schematic summary of the dynamic field model of the A-not-B error. The mo-
tor planning field is conceptualized as a continuous space of activation sites representing the ab-
stract parameters needed to plan a reach to the A location or to the B location. Note how activa-
tion is not on-off, but has a gradual rise and decay. These rise and decay times, we propose, may
play an important role in developmental changes in task behavior. The field receives various in-
puts and then integrates them to form a single decision. This requires that the visual inputs from
the task (upper left, representing two identical targets at A and B), the cue (upper right—a cue to
B), and the memory of the previous reaches (many reaches to A) be in the same parameter
space. This figure shows what happens after many reaches to A, which have built up a strong
memory to the A location, the infant receives the cue to B. In the field, the B cue is transient and
fades, while over the short delay, the A-side memory dominates. The infant reaches back to A.
reached to A on the A trials continued to reach to A on the B trials. Those who, for whatever reason, reached to B on the A trials were more likely to stay at B on the B trials. (Recently Marcovitch et al., 2002, also showed that the number of A trials affects perseveration.) In short, the infant’s history during the task mattered profoundly.

The Embodied Part

As predicted by dynamic theory, these experiments demonstrated that perseverative reaching emerges over time, as a memory for A-side reaches becomes so strong that it overshadows the new cue. The second dynamic prediction is that the behavior was a consequence of all of the components involved in reaching for a target. For instance, although the repeated reaches build up a habit, changes in infants’ posture, attention focus, or the relative colorfulness of the targets can all interrupt this habit (Diedrich, Highlands, Spahr, Thelen, & Smith, 2001; Smith et al., 1999). Indeed, the memory of the action also includes not only the spatial location of the reach and nature of the target, but also a trace of the actual movement, the trajectory of the arm in space. Diedrich, Thelen, Smith, and Corbetta (2000) dramatically demonstrated this by recording the actual movements of the hand as infants did a typical A-not-B task. They showed that, for infants who perseverated, the time-space paths of the hands actually become increasingly similar, suggesting that reach memories persisted long enough to influence the movement of the next reach. Moreover, manipulations such as adding or removing weights from the arms between the A-not-B trials acted to disrupt these motor memories and reduce perseveration (Diedrich, Thelen, & Smith, 2002).

U-Shaped Behavior in A-not-B

In the traditional formulations of A-not-B as arising from an incomplete object concept or from deficits in memory or inhibitory control, the clear prediction is that infants should perseverate more when they are younger: their object concept is less well-formed, their memories are poorer, and they can inhibit previous movements less well. The dynamic and embodied perspective led to the opposite prediction. Clearfield, Thelen, and Smith (2002) reasoned that if the motor memory of reaches contributed to A-not-B perseveration, then infants who could not form consistent reaches could not build up these repetition memories and would thus not perseverate. In other words, younger infants, who are unskilled reachers, should perseverate less not more. Perseveration should arise when reaching becomes stable: infants should look worse before they look better, but because of an improvement in a contributing component. Clearfield et al. (2002) also simulated this prediction using the field model by decreasing the memory input from each reach, as would result from varied and inconsistent reaches. With this change in the model parameters, they showed a U-shaped trend: younger infants perseverating less at the same delay at which older infants make the error.
Munakata (1998) made a similar prediction using a parallel distributed processing model with many similarities to the Thelen et al. (2001) model. She proposed that perseveration arises when 9-month-old infants' "latent" memories for A cannot compete with "active" memory traces for B. She assumed that younger infants would form weaker "representations" of the A targets, simulated by smaller recurrent weights in the network. When the recurrent weights are small, there is not enough memory to form competitive A memories and infants do not perseverate. Perseveration increases and then decreases as a function of age-related changes in strengths of representations.

Both the Thelen et al. (2001) and Munakata (1999) predictions of U-shaped behavior were confirmed in the Clearfield et al. study. These authors followed a group of 14 infants from 5 to 8 months. Each month they tested them with a lids-only (no hidden object) A-not-B task. The no-hidden object task was essential because infants will not learn to uncover a hidden object before about 7 months of age. However, they can reach for targets. The stimuli were identical to those used in Smith et al. (1999) in the no-hidden object condition: brown "lids" on a brown box. (Recall that 8- and 10-month-old infants made the A-not-B error at the same rates with and without a hidden object with these stimuli.) Infants received six trials at A, four of which were training trials where the lid was first placed forward on the box and then successively moved back until it was next to the B lid. They then

![Graph](image)

**FIGURE 2** Percentage of infants correct on the first B trial in a no-hidden object A-not-B task as a function of age from Clearfield and Thelen (1998).
received two additional A trials and two B trials. There was a 3-sec delay between hiding and reaching on the B trials for all ages.

As predicted, at younger ages, infants persevered less: reliable perseveration appeared only at 8 months. This is shown in Figure 2. Even though there was a 3-sec delay at all ages, at 6 and 7 months, infants were reaching randomly. At 5 months, they were actually correct at B, but only 6 of the 14 infants completed the task at this age. The remaining 8 infants refused to reach when faced with the two targets, although in pretesting, they readily reached for just one target. But those who did reach were likely to be correct, even with a 3-sec delay. These results further suggest that other factors in addition to remembering the cue over the delay are responsible for perseveration. Specifically, the strength of the remembered trace of the reach between each trial may account for the developmental effect. Younger infants are poor reachers and their reaches are erratic. Because the reaches are not reliably repeated, infants form a weaker reach memory at the A location and thus are less likely to perseverate at B. It is also likely that the youngest infants were more confused by the identical targets and less able to form a decision when the perceptual information is ambiguous, leading to no reaching at all.

Reaching perseveration at 8 to 10 months in the typical A-not-B task, therefore, arises from a confluence of factors: an unfamiliar situation with two identical targets, the need to remember a cue over a short delay, repeated reaching toward one target, and reaches that are stable enough to leave a perceptual motor trace. Because these are properties of general processes of perceiving, deciding, remembering, and moving, changes in task difficulty, timing, and memory demands can produce similar perseverative behavior in older children (and even in adults), as we explain below.

We next describe another U-shaped behavior that appears in early word learning—nearly a year later than the classic A-not-B. Again, we show that the appearance of regression is an emergent property, which, in this second example, concerns the natural dynamics of vocabulary growth, the child’s history of practice with individual words, and the demands specific to the task of naming objects. Following this, we offer a common explanatory account of perseverative responding in the A-not-B task and similar tasks in older children, and in everyday picture book naming activities, based on a dynamic model.

Perseverative Naming of Familiar Objects

Between 12 months and 2 years of age, children make a dramatic transition from not talking to talking. During this time, there is a marked increase in the number and rate of new words acquired and produced. The majority of these first words are object names, although children also learn words for actions and events, as well as names for the relations and properties of common objects (Bloom, Tinker, & Margulis, 1993; Gentner & Boroditsky, 2001).
In the early period of language learning, young children sometimes mistakenly use one word in the place of another when attempting to name an object. Previous research has suggested several reasons why children might call an object by another name, including faulty hypothesis testing concerning the meaning of words (Bowerman, 1978; Clark, 1973; Vygotsky, 1962) and pragmatic solutions to a communication task given limitations in vocabulary size (Bloom, 1973; Hoek, Ingram, & Gibson, 1986). The literature has discussed these naming errors under the general rubric of overextension errors. Some researchers have suggested that errors are particularly characteristic of the so-called vocabulary spurt, a period near the end of the 2nd year when children seem to name everything in sight (Macnamara, 1982; Rescorla, 1980). Others suggest that overextensions continue and even increase after the onset of the spurt (Dromi, 1987). However, it is unclear whether there is a single phenomenon underlying these errors or perhaps several related phenomena with their own causes and developmental trajectories (Gershkoff-Stowe, 2001).

Gershkoff-Stowe and Smith (1997) captured changes in children’s spontaneous naming over a 6-month period, beginning when they were about 15 months of age. Their research thus spanned the time just before, during, and just after the vocabulary spurt. Children came to the laboratory with their parents at 3-week intervals. Together, they looked at and named familiar objects in two picture books. In addition, at each session, the experimenter recorded the number of new words the child spoke at home, as measured by parent diaries. From these diary data, the experimenter estimated when children first reached the marked increase in vocabulary growth that is characteristic of the vocabulary spurt.

The central finding was a brief, though dramatic, rise and fall in naming errors at a time when the rate of productive vocabulary growth was maximal for individual children. Based on parent diaries, this developmental point occurred, on average, when children had approximately 75 words in their productive vocabulary. Moreover, close analysis of the particular character of the error revealed that the majority of the errors involved words that were known to the child. That is, unlike the overextension errors children sometimes make, most errors occurred when the child mistakenly used a wrong word to name a familiar object—one that had been named correctly many times before. In addition, Gershkoff-Stowe and Smith (1997) found that the errors were mainly perseverative in nature; they involved the repetition of a word just previously said by the child. For example, the child would point to a picture of a horse and say “horse” and then point to a picture of a shoe and say “horse,” even though shoe was a word correctly produced on prior occasion. The errors thus appeared to be principally due to difficulties in retrieving the desired word from lexical memory. These findings, together with the fact that the errors were closely tied to the onset of vocabulary spurt, suggested that they stemmed from weaknesses in the processes associated with the correct retrieval of words from a newly forming and rapidly expanding lexicon.
This early period of heightened error also corresponded to an initial increase in the rate of children's talking in the laboratory. Importantly, however, although both rate of talking and productive vocabulary growth continued to rise in the weeks that followed, the proportion of naming errors was specific to the onset of the spurt, and not before or after. Thus it was not the case that children made many errors when they had few words in their vocabulary, or when they engaged in much more talking in the laboratory. Rather, the majority of the errors occurred when children first showed a significant increase in the number of new words they produced. We can conclude, then, that rate of vocabulary growth acted as the control parameter for the temporary rise in errors at the time of accelerated development. However, it bears emphasizing again that in a dynamic model, no single developmental event can be considered the causal factor underlying the increase in naming errors. Because behavior is so highly assembled from the confluence of different but interrelated parts, we cannot say that one component takes causal precedence over another. Rather, its emergence is seen as a product of multiple, contingent processes, each with its own developmental history. This included the child's familiarity of the word, as well as the number of times the word was said just prior to the error (Gershkoff-Stowe, 2002). Also important were the features of the objects themselves, for example, their visual properties, location on a page, how often they were presented for naming, and their semantic relatedness.

Together, these multiple processes conspired to produce perseverative naming. Such behavior, moreover, is not specific to novice word learners. Perseverative naming is also observed in older children acquiring many new words (Gershkoff-Stowe, 2002), in normal adult speakers under speeded naming conditions (Dell, 1986), and in adult aphasics (Dell, Schwartz, Martin, Saffran, & Gagnon, 1997). For these different populations of speakers, the control parameter is likely to vary. At critical times and in certain contexts, a small change in one or more components can lead the system to a period of instability; at other times, similar changes may have negligible effects on the stability of the system.

In sum, the accuracy of naming objects, like reaching in the A-not-B task, is a state that cannot be inferred from the child's knowledge alone. Such a view has been predominant in explaining children's overextension errors (Clark, 1993). Rather, the likelihood of a correct response—whether in the context of solving a problem, reaching for a hidden object, or learning a new word—is the product of an interaction between internal processes and external conditions. In the case of U-shaped changes in perseverative naming, we have suggested that the rate of error depends on critical changes in productive vocabulary growth, frequency of talking, immediate prior repetitions, and the properties of objects to be named. More, generally, we have suggested that nonlinear, U-shaped behavior arises from the interaction of multiple processes and events that themselves change over developmental time.

In the next section, we offer one possible mechanism for U-shaped behavior to explain reaching in the A-not-B task and naming in the context of picture book
reading. In both cases, we show that perseveration is an emergent result that de-

pends on the nature of the task and the internal dynamics of the child.

Mechanisms in Perseveration

U-shaped changes in behavior can be represented by the strengths of activation of a
memory and their activation curves. Consider, first, the A-not-B task and the mem-
ory of consecutive reaches to A and to B. In a newly reaching infant of 4 or 5
months, reaches are slow to activate, and less frequently performed. Infants will
look at the target sometimes for several seconds before the movement begins, and
when targets are unfamiliar, they often will not reach at all. We can represent early
reaches in Figure 3A, as slow to activate and slow to decay. Consequently, they
leave relatively weak traces from one trial to the next. As reaches become more sta-
ble and repeatable, they are also activated more quickly, have a stronger overall
level, but still take some time to decay (Figure 3B). They will leave a much stron-
ger memory trace. Indeed, as reported in Thelen, Corbetta, and Spencer (1996) and
Clearfield et al. (2004), there is a quite dramatic improvement in reach-
ing—smoother, straighter trajectories and less variability—at about 7 or 8 months,
the ages when reliable perseveration appears. Finally, as reaching becomes even
more skilled, reaches are activated very quickly, but also decay more quickly (Fig-
ure 3C).

What happens, then, in a typical A-not-B situation, when the experimenter asks
the infants to reach to an identical target soon after the first reach? In the case of
delay reaches, the memory trace is so weak that very little activation is left to influ-
ence the second reach, and there is insufficient carry-over to build a habit to com-
pete with the B cue. Infants follow the cue and are correct. This effect is accentu-
ated if the interval between reaches is long, which happens in young infants
because they take a long time to reach when they see the target, as if they need

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{threeactivationcurves.png}
\caption{Activation and decay of a behavior (e.g., reaching, naming) at three skill
levels.}
\end{figure}
more time to activate their movements toward a goal (Figure 4A). When reaches become more stable, however, they leave a stronger trace, but if they overlap, there is considerable shared activation. As infants become better reachers through repeated experience reaching, their cue-to-reach “reaction time” also becomes faster, inter-reaching intervals are shorter and the overlap is accentuated. This sets up the condition for perseveration (Figure 4B). Then again, when reaching is skilled, rapid decay of activation means that there is little carry-over and reaches can follow one another quickly or slowly without the memory build-up that leads to perseveration (Figure 4C).

We can similarly represent word retrieval processes, using the same activation and decay curves. As suggested by adult studies of lexical access, the frequency of a word importantly affects the speed and accuracy with which words are retrieved for naming (Forster, 1990). In that literature, frequency of a word in language is used as an estimate of its frequency of experience by an individual, in other words, the degree to which a word is practiced. The more practice a speaker has using a word, the more robust the retrieval of that word will be. Early in development, when children have very few words in their productive lexicon, every word is likely to be of low practice by adult standards. This is because the lifetime history of individual words being retrieved and produced is extremely short. Thus the course of retrieval for early words is likely to involve a low level of activation and a slow rate of decay (Figure 3A). Later in development, as children go from having few words to having many words, some of those words will now be more stable and of a higher level of activation (Figure 3B). This is because children will have had more opportunities to practice saying the words they know. However, these words may still take some time to decay. Finally, in the post-spurt period, children will have many more words, some of which are low practiced, but many more of which have now been retrieved and
spoken many times before. Accordingly, the activation and decay function will peak swiftly and decay rapidly (Figure 3C).

Consider, next, how differences in the strength of activation for individual words might affect the ability to retrieve two words in close succession. Here, Figure 4 represents the time course of activation and decay of two consecutive words. In the period before the spurt, children are talking little, and there is considerable time between each utterance. Thus there is little opportunity for one word to interfere with another (Figure 4A). At the time of the vocabulary spurt, children are talking more often and thus retrieving words closer together in time. This means that the slow rate of decay from the first word may interfere with the retrieval of the second word (Figure 4B). In the post-spurt period, children continue to add new words to their productive vocabulary at a rapid rate and to retrieve words in close temporal proximity. Indeed, it is at this time when multiword utterances first appear (Bates & Goodman, 1997). Now, however, the activation level for each word has increased, and the rate of decay is considerably faster. Thus, there is less opportunity for the first word to interfere with the retrieval of the second word. Figure 4c shows the faster and more robust processes associated with retrieving words that are high practiced in the post-spurt period.

What we have suggested, then, is that nonlinear, U-shaped behavior arises from continuous changes in system components. Similar to infant stepping, the underlying changes are not specific to either perseverative reaching or perseverative naming, but come about from basic processes needed to activate, perform, and remember, and from improvements in these processes from practice.

In the A-not-B error, perseveration may occur independently of infants' "representations" of hidden objects, and seems not to depend solely on keeping the toy in mind over the delay between cueing and reaching, because infants as young as 5 months old can do this. Indeed, as the task becomes harder, older children and adults will also perseverate. For instance, Spencer et al. (2001) showed that 2-year-olds perseverate to location A when toys are hidden in a sandbox and where the delay was increased to 10 seconds. The sandbox offers fewer cues to the toy's location than in the typical task, where the targets are marked by covers or lids. As in younger infants, perseveration was strictly a function of the number of A reaches. Likewise, Schute and Spencer (in press) demonstrated that 3-year-olds' reaching is also biased toward previous reach memories in an even more challenging A-not-B type task. Perseverative reaching can arise for many reasons: here we suggested that changes in motor activation and memory could account for U-shaped behavior in young infants, but children's ability to sustain location memories over delays may underlie changes at other ages. Similarly, changes in location memory can itself have different underlying causes, including those involved in more efficient perceptual learning, attentional mechanisms, and the development of excitatory and inhibitory networks.
In the picture book naming task, perseveration arises from multiple processes related to the influence of word frequency and the relative differences in the cumulative strength between lexical competitors. There are several reasons why children show a particular vulnerability to interference from a recently retrieved word during the developmental period when vocabulary growth begins to accelerate. More words in the lexicon increases the opportunity for competition during retrieval (Charles-Luce & Luce, 1990). In addition, increased word production results in children retrieving words closer together in time. As suggested by Wijnen (1990), there is a brief period of repetition and substitution errors as children begin to produce multiword combinations between the ages of 2 and 3 years.

Recently, Gershkoff-Stowe (2002) showed that practice naming objects can reduce the likelihood of perseverative error during the period of accelerated vocabulary growth. In one experimental training study, children 15 to 21 months of age were presented with two individual training phases at each session every 3 weeks. In the first Standard Practice training phase, children learned the names of 12 experimental objects by hearing and saying their names in the context of looking at a picture book with their parents. In the second Extra Practice training phase, children received extra training in hearing and saying 6 of those 12 object words. Thus

![Graph](image)

**FIGURE 5** Mean frequency of naming errors for high and low practice words in three developmental periods of vocabulary growth in Experiment 1 of Gershkoff-Stowe (2002).
there were 6 high practice and 6 low practice words with which to compare children's naming errors.

As shown in Figure 5, children consistently made more errors with the experimental words when they were less practiced than when the words were highly practiced. Moreover, errors of low-practice words rose sharply at the time of the vocabulary spurt, while errors of high-practice words did not. The results thus demonstrated that with repeated practice retrieving and producing individual words, the words became stronger and more resistant to interference from lexical competitors. These findings are consistent with studies of normal and aphasic speaking adults in which extended practice repeating difficult tongue twisters resulted in significantly fewer production errors (Dell, Burger, & Svec, 1997; Schwartz, Saffran, Bloch, & Dell, 1994).

In contrast to the widespread view that changes in cognition result from transformations in conceptual knowledge, we have argued that the production of a correct response—whether in the context of solving a problem, reaching for a hidden object, or learning a new word—can not be inferred from knowledge alone. Rather, its emergence is a product of multiple, contingent processes both internal and external to the child.

CONCLUSIONS

Throughout this article, we have emphasized the emergent nature of the U-shaped development of infant stepping, perseverative reaching, and early object naming. In each case, the seemingly regressive behavior appears because of a particular confluence of developmental history and task. In no sense is the regression "in" the child alone as though developmental progress went backward or skills were lost. Rather, these behaviors are seen "softly assembled" from basic processes under rather special task circumstances. That perseverative reaching and naming errors are themselves fragile and context dependent is further evidence of their dynamic character.

U-shaped behavior is important not only because it seems to defy the progressive nature of development, but also because it provides such a clear window on the nature of developmental process itself. It suggests that development in any domain cannot be considered as encapsulated or modular, but must be constituted from the ensemble state of the organism-in-context. If perceptual and motor skills, memory, and sheer practice play a role in these early examples, these same components must surely influence behavior in other domains as well, including problem-solving skills, social inference, and so on.

A second lesson from U-shaped change is that the distinction between competence and performance is not viable. What is the child's "real" competence in the fragile A-not-B or object-naming tasks? The question cannot be answered because
every performance is constituted in the moment from a rich developmental history and a specific task. For example, infants are said to have "innate" and core abilities to count and add and subtract events (Wynn, 1995), but older children fail at the very same task (Mix, Huttenlocher, & Levin, 1996). Closer examination of the tasks suggests that surface behavior may result from different underlying processes. In particular, some have suggested that the structure of the tasks used to probe infant core abilities may reflect much simpler perceptual processing (e.g., Clearfield & Mix, 1999; Haith, 1998), and that assumptions about core abilities continuous with later mathematical skills are unwarranted.

In sum, U-shaped behavior has served an important role in directing our attention to the complexity and nonlinearity of development. Because this behavior flies in the face of our conventional assumptions, it has compelled us to take a much closer look at the mechanisms producing change. This kind of close look can only be helpful for understanding all developmental change, whether they contain regressions or not.

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