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How the Brain Learns

Growth Cycles of Brain and Mind

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Changes in thinking and learning relate to physical changes in the brain. The repeating patterns of these changes suggest common growth cycles in behavior and in the brain—a cyclical property that explains the remarkable human capacity for plasticity.

Recent research and theory in cognitive neuroscience have produced insights into how the development of the brain, especially the cerebral cortex, relates to thinking and learning (Fischer & Rose, 1996; Thatcher, 1994). These insights have important implications for educational practice and policy (Case, 1993; Fischer & Bidell, 1997). Prior conceptions typically treated development as a sequence of stages, like the steps of a ladder, but current work replaces that overly simple notion with the rich biological concept of a recurring growth cycle: Both behavior and the brain change in repeating patterns that seem to involve common growth cycles (Case, 1991; Fischer, 1980).

These growth cycles repeat several times between birth and 30 years of age. Each recurrence produces a new capacity for thinking and learning that appears to be grounded in an expanded, reorganized neural network. Humans have a new opportunity for relearning skills and reshaping networks that they missed learning in earlier cycles. This cyclical property seems to explain the remarkable human capacity for plasticity, including recovery from damaging environments and neural injuries, especially when later development occurs in a benevolent, nurturing environment (Diamond & Hopson, 1998).

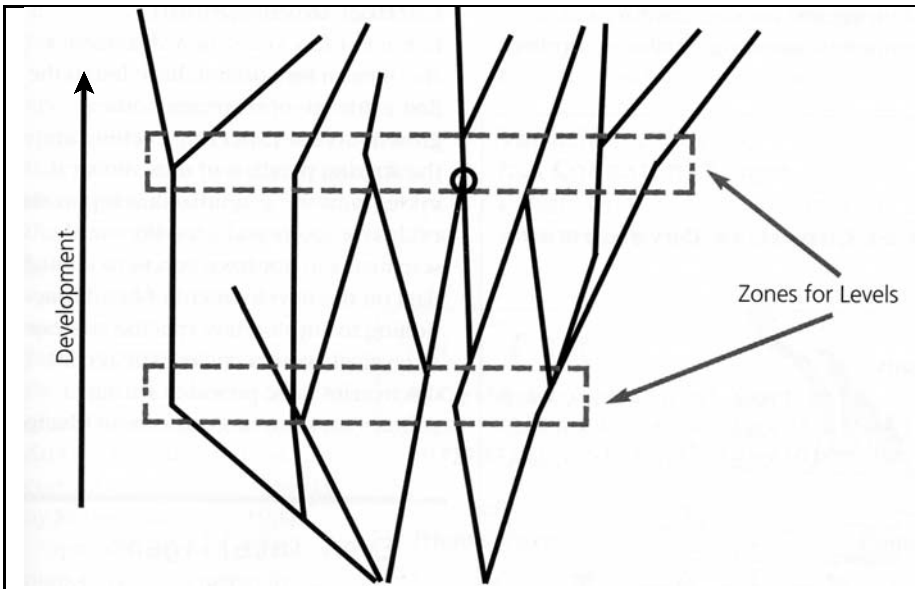
On the side of thinking and learning, the cyclical changes in capacity are not evident in everything that children or adolescents do because most of their acting, thinking, and learning do not push the limit of their capacities. Each new round of the cycle, called a developmental level, is most evident in a person's optimal level, the most complex skill or understanding that he or she can produce. Usually a person produces this optimal level only with strong contextual support, like that from a teacher, a tutor, or a text. Without such support, most thinking and learning occur at lower levels, not at the optimal level.

Cycles of Cognitive Development and "Stages"

A prerequisite for understanding our argument is to purge the classical conception of development, which treats thinking and learning as a progression through a series of stages that form steps in a developmental ladder. Instead, in the dynamic skills framework, development is much more variable and flexible and shows complex, dynamic patterns of change with many of the properties described by mathematical theories of complexity, chaos, and catastrophe (van der Maas & Molenaar, 1992; van Geert, in press).

A useful metaphor for some of the dynamic properties is a developmental web, with thinking and learning changing in parallel along multiple strands or domains, as reflected in such concepts as Gardner's (1993) multiple intelligences. A child develops a set of spatial skills and a separate set of musical skills, as illustrated by the strands on the left and right, respectively, of the web in Figure 1. When a new developmental level emerges, optimal performance along most strands shows discontinuous change, reflected in growth spurts and reorganizations, which are marked by changes in direction, forks, and intersections of the strands in the web. These changes do not occur all at once, but they are distributed across a specific age period or zone marked by the boxes in Figure 1. With the emergence of each level, a child can build a new, more complex kind of skill or understanding in diverse domains.

Figure 1. A Developmental Web with Zones of Emergence of Two Skill Levels in Two Domains



A child develops skills and knowledge along multiple independent strands for separate tasks and situations. The diagram shows how a child develops skills for several strands in the spatial and musical domains, which are mostly separate. Development of a new skill level in both domains produces a cluster of forks, intersections, and changes in direction across most strands, as indicated by the gray boxes for two successive levels. Skills relating the spatial and music domains intersect at one point (marked by a small circle) when the child begins to learn musical notation, which requires an integration of spatial and musical skills.

Each new level produces a cluster of spurts in optimal skill and understanding across many domains in a particular age period, a cognitive surge analogous to the spurts in height that children periodically show. Unlike height, however, cognitive spurts are evident only under optimal support conditions, not across the entire array of children's behaviors. A good teacher will bring them out in the classroom, but they will typically not be evident when a child is working or playing alone or without support.

Development involves a long series of new levels, each constructed independently in parallel for each strand or domain. The first ones develop in the child shortly after birth, and they continue to emerge until he or she reaches approximately 30 years of age. These spurts in capacity seem to be grounded in two recurring growth cycles. The shorter-term cycle involves constructing successive *levels* of skill or understanding, moving from single units, to mappings relating a few units, to systems relating multiple units, and finally to the formation of a new kind of unit that reorganizes and simplifies systems. This reorganization and simplification in turn is nested in a longer-term cycle, moving through four different forms of action and thought called *tiers* (reflexes, actions, concrete representations, and abstractions) (Case, 1991; Fischer, 1980). Both cycles seem to be based in the growth of neural networks, involving a combination of changes in connections among regions of the cortex and changes in brain activity in particular regions.

A metaphor that illustrates the nature of the long-term cycle of tiers is the construction of a cube or other solid figure in four levels, as shown in Figure 2. To build a cube, we first combine single points to form lines. We combine lines to form squares, then squares to form cubes. The cube in turn is a new building block that begins the process again, as we combine cubes to form lines, and so forth. The shorter-term cycle occurs within each level.

If we focus on only the leading edge of change—the zone of emergence for each optimal level—we can summarize the development of skill capacities and neural networks as shown in Figure 3. The four forms of action and thought (tiers) are on the left of the figure, and the skill levels for each tier are on the right. Capacities to build reflex skills (species-specific actions and perceptual patterns) emerge in the first dozen weeks of life and eventually produce the first sensorimotor actions (grasping, looking, walking, eating, and the like).

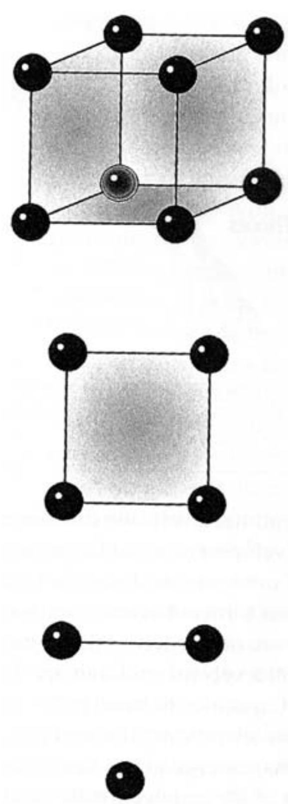
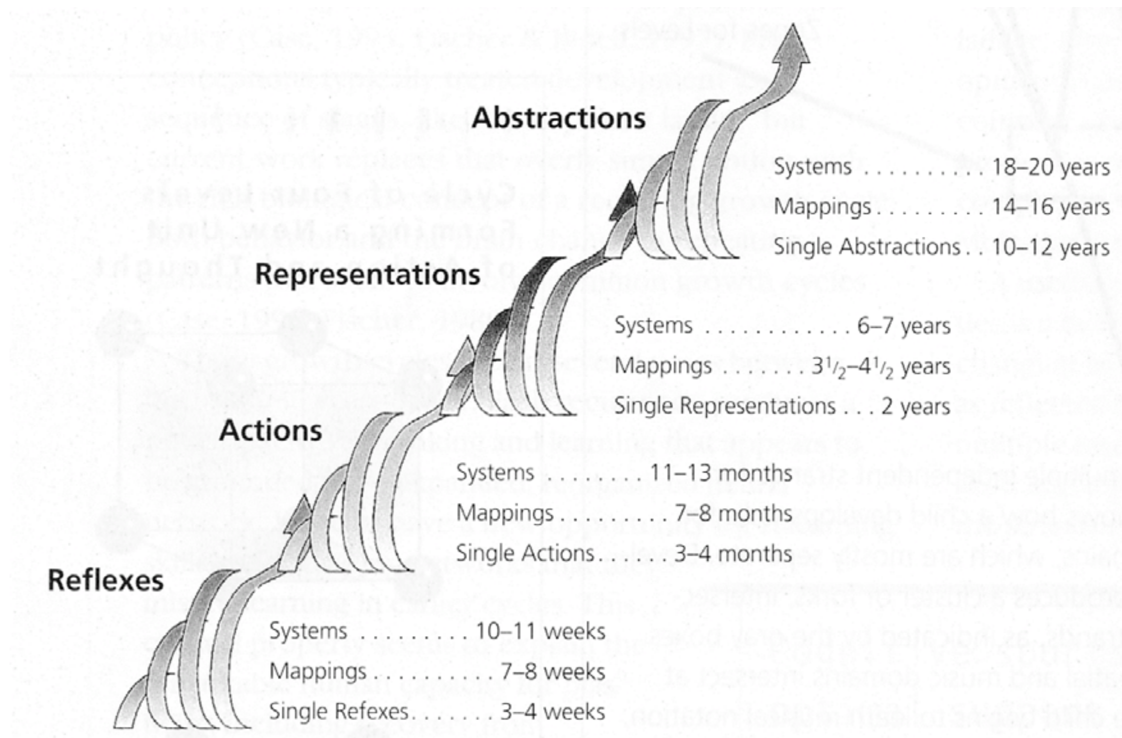


Figure 2. Cycle of Four Levels Forming a New Unit of Action and Thought

Figure 3. Nested Developmental Cycles: Four Tiers Composed of Levels of Cognitive Development



Ages indicate approximate time at which that level emerges under optimal (high-support) conditions, with most skills remaining below that level in ordinary functioning. Tiers are listed on the left, and levels within each tier are listed on the right.

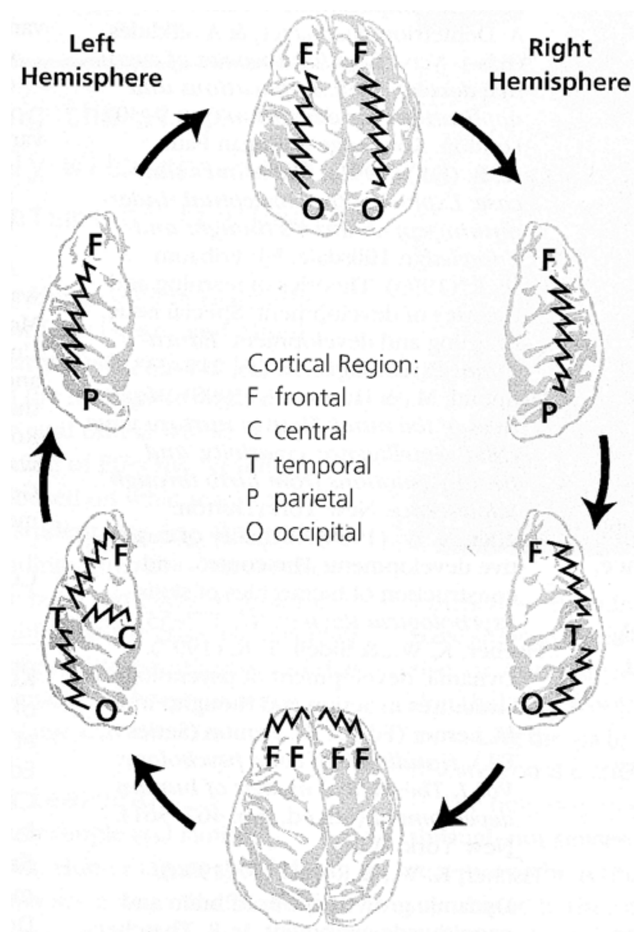
Capacities for building more complex sensorimotor actions emerge between 3 months and 2 years and eventually create the first concrete representations (for example, forming sentences, symbolizing specific people as independent agents, naming categories of emotions, counting numbers). Optimal levels for representational capacities develop during childhood, between 2 and 12 years. Eventually a child understands his or her first abstractions (such as literary and mathematical concepts; personality and motivational characteristics; concepts of society, law, and philosophy). Optimal abstraction capacities appear between 10 and 25 years of age and produce the capacity to build principles relating multiple abstractions (such as evolution by natural selection, reflective judgment, the Golden Rule). The right part of the diagram shows the second cycle of specific skill levels and their approximate ages of emergence.

Nested Cycles of Cortical Development

In the last few years, new discoveries about brain functioning have led to the first evidence of recurring cortical growth cycles. Especially exciting are the striking parallels of these cortical cycles with the cognitive-developmental cycles for levels and tiers. Previously, scientists did not have access to enough data on the development of brain functioning to support any specific analysis of cortical growth cycles. The recent discoveries have provided strong sources for analyzing patterns of change in cortical activity and connection. Studies in three countries have found similar cyclical patterns of cortical change with age in childhood and adolescence (Bell, in press; Fischer & Rose, 1996; Matousek & Petersén, 1973; Somsen, van't Klooster, van der Molen, van Leeuwen, & Licht, 1997; Thatcher, 1994).

Figure 4. A Cycle of Growth of Cortical Connections for

Each Level of Network Formation and Skill Development



First, the amount of energy in the electroencephalogram (EEG), which indicates electrical activity in the cortex, shows systematic spurts that closely parallel the spurts observed in optimal levels for cognitive development. In addition, connections among cortical regions, which are measured by EEG coherence (the correlations of wave patterns between regions), demonstrate qualitative shifts at the same age periods. The ages for these two kinds of brain changes are remarkably similar to those listed in Figure 3 for cognitive levels.

Second, both types of measures—energy and connection—show not only spurts but also specific growth cycles that parallel the two cognitive cycles shown in Figures 2 and 3: one cycle for the development of new forms of action and thought and a second cycle for the development of specific skill levels (Fischer & Bidell, 1997). Figure 4 shows the cycle for the development of skill levels and is based on data for growth spurts in cortical connections reported by Robert Thatcher (1994).

Spurts in cortical connections move systematically around the cortex in a similar pattern for each skill level, presumably reflecting changes in neural networks. The jagged lines indicate cortical locations that show the largest growth in connections, and the arrows specify the sequence in which growth moves around the cortex. Spurts in the growth of connections begin with front to back connections in both hemispheres and then shift to involve mostly right hemisphere connections. Within the right hemisphere, they gradually move from long distance connections to more local connections. Then they shift to the left hemisphere, where they move gradually from local to long distance connections. When the spurts reach front to back in the left hemisphere (and simultaneously in the right), the process starts over again for the next level.

The cycle in Figure 4 repeats for every level, and three occurrences of this cycle are nested in the longer-term cycle for each tier. That is, in Figure 3, the cycle of connections occurs for every loop in the shaded spiral arrows.

Variation in Levels, not Consistent Stages

Unfortunately, we can easily misconstrue this new cycles framework for understanding development and learning as a model of stages. Children and adults do not develop in stages, although optimal levels of skill do show relatively sudden spurts and reorganizations. People vary enormously in the skill levels they use every day, only occasionally functioning at their optimal level, as teachers see with their students. Full development of each new level emerges gradually over a long period. Even under optimal conditions in a single domain, such as spatial reasoning, the concurrent zone spans time. There is no sudden transformation, no instant change at, say, 10 years of age to understanding abstract concepts about space. Instead, children show a cluster of changes over several years, such as 10 to 12 years for optimal level with spatial concepts. Across several domains, such as spatial and musical concepts, the age span is even longer.

In ordinary functioning, without optimal support, students vary greatly in their skill levels. They typically perform at lower levels, because in everyday life, support for optimal skills seldom exists. Educators need to teach to ordinary functioning, not only to optimal levels, because students need to use what they learn in the many situations where there is no optimal support. To sustain a high skill level without support, a student requires extensive practice and experience. Even intelligent adults have to work for long periods to master new abstract concepts in unfamiliar domains, for example, when teachers extend their knowledge to non-Euclidian space, new musical styles, or the mechanisms of neural networks. Capturing the educational implications of growth cycles requires analyzing the full range of variation in levels of skill and understanding, not focusing primarily on optimal levels or growth spurts (Bidell & Fischer, 1992).

Implications for Educators

These findings and concepts have important implications for the development of thinking and learning.

1. Cognitive growth and brain growth both show remarkable resilience and plasticity when children live and learn in adequate environments. The cyclical nature of cortical growth and optimal cognitive development seems to foster these characteristics of resilience and plasticity.

2. Brain development involves a recurring growth cycle of neural networks and learning, in which a child not only learns skills and concepts once, but also relearns and reworks them anew at each successive optimal level.
3. Children (and adults) function at multiple levels of skill and understanding, even for a single topic or domain. Their concepts and skills vary across a wide range of levels, and normal functioning is usually not at optimal level.
4. An individual's level of skill and understanding depends pervasively on contextual support for high-level functioning. Effective teaching and, at later ages, effective textual presentation powerfully support high-level functioning. Removing the support leads to a natural, rapid drop in the level of understanding.
5. Educators need to focus on teaching children at lower, as well as at optimal, levels because independent learning and thinking usually occur at lower levels, with optimal functioning limited to supportive situations.

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