Siegler, R. S. (2016). How does change occur? In R. Sternberg, S. Fiske, & D. Foss, (Eds.), *Scientists making a difference: One hundred eminent behavioral and brain scientists talk about their most important contributions* (pp. 223-227). New York: Cambridge University Press.

# 48 How Does Change Occur?

*Siegler, Robert S.*

For as long as I can remember, I've been fascinated by change. How does an infant turn into a toddler, and then a preschooler, a child, an adolescent, an adult, and, eventually, a senior? What leads to changes in people's character, their intellect, their relationships with other people? What, if anything, unites evolutionary processes, regardless of whether they involve the evolution of species, the evolution of businesses, the evolution of national policies, or the evolution of a person's thinking about a specific topic?

This fascination with change led me to study the development of learning and problem-solving during childhood. Within the human lifetime, many of the greatest changes are seen from birth through adolescence; indeed, childhood can be defined as the period of life in which positive change is most dramatic.

Most of my research on learning and problem-solving during childhood has focused on the development of mathematical thinking. This interest began in childhood, when I became intrigued by the statistics on the backs of baseball cards: batting averages, hits, home runs, win-loss percentages, earned run averages, and so on. I spent innumerable hours engrossed in identifying from these statistics the best player at each position and which teams were most likely to win the World Series.

A variety of factors led to my pursuing this early interest in my research. When I began to do research, Piaget's theory, which was built in large part from observations of mathematical and scientific thinking, was the dominant approach to cognitive development. My early research was intended to show that Piaget had underestimated children's capacity for problem-solving and learning in these areas. Although the results of my early research supported this hypothesis, observing how tenaciously young children clung to their misconceptions about scientific and mathematical concepts led me to an enduring appreciation for Piaget's genius in designing revealing tasks, where answers and explanations on a single trial could lead to insights about children's thinking.

My appreciation for this aspect of Piaget's genius led to the discovery that I consider to be my most fundamental – fundamental in the sense that it provided the foundation for numerous subsequent discoveries. The discovery was that we can accurately assess individual children's problem-solving strategy on each problem by video-recording ongoing overt behavior during the problem and then immediately afterward obtaining the child's explanation of how he or she solved the problem. Combining the two types of data is more effective than using either alone; children sometimes do not generate any overt behavior, in which case the explanation can be used alone, and children sometimes cannot explain what they did, in which case the overt behavior can be used alone.

The first dividend of this discovery was to show that many models that seemed accurate when evaluated against data averaged across participants and problems were oversimplified or flat-out wrong. In some cases, the previously accepted model proved accurate on most problems but not on many others; in other cases, the previously accepted model proved accurate on a minority of trials; and in yet other cases, the model failed to accurately depict any individual children's thinking on any single trials, but, rather, was an artifact of averaging the data that arose from different approaches.

A second dividend of the trial-by-trial strategy assessments was richer and more accurate descriptions of children's problem-solving than was previously possible. Rather than all children of a given age using a single strategy to solve a given task, or some children using one strategy and other children using a different one, individual children have been found to use between 3 and 10 strategies on a wide variety of tasks. The tasks where such varied strategies are used include arithmetic, spelling, reading, scientific reasoning, attention, memory, tool use, estimation, inferences about other people's thinking, descending down ramps, and many others. For example, when adding small numbers, the same first grader might count from 1 on the first problem (e.g., "2+5 = 1, 2 – 1, 2, 3, 4, 5 – 1, 2, 3, 4, 5, 6, 7"), count from the larger number on the second (e.g., "2+7= 7, 8, 9"), draw an analogy to a related problem on the third (e.g., "2+9 = 2+10–1"), and retrieve the answer on the fourth (e.g., "2+3=5").

Appreciation of this strategic variability made possible a more nuanced portrayal of development than previously. Rather than development involving use of one way of thinking for a prolonged period, then a sudden hard-to-understand shift to a different way of thinking, and eventually another sudden shift to a third way of thinking, development was found to involve use of varied strategies at each age, with cognitive growth coming from increased use of more effective strategies, decreased use of less effective strategies, increasingly efficient execution of all of the strategies, and discovery of novel strategies. To continue with the example of simple addition, between kindergarten and second grade, counting from one becomes less common, retrieval from memory becomes more common, counting from the larger addend at first becomes more common and then becomes less common, and children discover that they can draw analogies to tie problems (e.g., "if 3+3 equals 6, 4+3 must equal 7"). Execution of all of these strategies becomes faster and more accurate during this period.

Discovering this strategic variability raised a new question: How do children (and adults) choose among the varied strategies that they know and use? There had been no reason to ask this question when people believed that children only used a single strategy at a single time. However, when the extent of strategic variability was documented, whether children chose wisely among problem-solving approaches became an important issue.

It turned out that children and adults usually do choose wisely. They often use a simple but effective rule of thumb for choosing among alternative strategies: Use the fastest strategy that you can execute accurately. Thus, if children can accurately retrieve answers to problems, they usually will solve the problems via retrieval, because retrieval is very rapid. On the other hand, if they cannot accurately retrieve the answer to a problem, they will more often use slower but more accurate strategies. In the addition example, even kindergartners usually retrieve the answer to 2+2, but on problems such as 2+5, they are more likely to count from one. These patterns are rarely all or none, though. Even college students use strategies other than retrieval to solve roughly 20 percent of single digit addition problems, and do so roughly half the time on problems such as 6+9.

Ability to assess strategy use on each trial also made possible microgenetic studies. These are experiments in which children are given greater amounts of relevant experience than is typical at their age, and their learning is followed on a trial-by-trial basis. This allows identification of a given child's discovery of new strategies, as well as the events that led up to the discovery and how it is generalized beyond its initial use.

Microgenetic studies have yielded a variety of consistent findings. One is that immediately before a discovery, performance usually becomes more variable. Children use a greater range of strategies, they generate short-lived transition strategies that often have elements of the more enduring discovery but are less effective, their solution times vary more, and they often have unusual difficulty explaining what they are doing. Another common finding is that even the most advantageous new strategies are often generalized slowly, with less effective previous approaches persisting for extended periods of time, even when children can explain why the new strategy is better. A third frequent observation is that newly discovered strategies that are very advantageous relative to alternatives tend to be generalized more rapidly than new strategies that are only somewhat better than previous ones.

My interest in numerical development, in the process of change, and in using psychological science to do some good in the world has led to my becoming increasingly interested in applying research to improving mathematics education. When children begin school, their numerical knowledge already varies greatly. Children from impoverished urban families typically start school already a year or more behind children from middle-income backgrounds in terms of numerical knowledge. These early differences seem to have long-term consequences: Four-year-olds' numerical knowledge predicts math achievement test scores in high school, above and beyond other relevant factors such as children's IQ and parents' income and education.

A very large amount of research indicates that people and many other animals organize numerical knowledge in a way that resembles a mental number line, with smaller numbers on the left and larger ones on the right. Preschoolers from low-income backgrounds, however, often have not yet organized numbers in this way. To help them do so, Geetha Ramani and I devised a numerical board game that had 10 squares in a row, with the numeral "1" at the left and "10" at the right. In playing the game, a child and an adult would alternate spinning a spinner and moving their token 1 or 2 spaces in accord with the spin; the first one to reach 10 would be the winner. Players were required to say the number in each square as they moved their token through it; thus, if the spin stopped on "2," a child whose token was on "3" would need to count "4, 5." The adult helped the child count when necessary. This game was expected to help children form a mental number line, because it would provide non-verbal cues to the sizes of the numbers. For example, it would take twice as many hand movements, twice as many counts, saying twice as many number words, and moving the token twice as far to reach 8 as to reach 4. Thus, playing the game provided visual, auditory, motor, and time-related cues to the sizes of the numbers.

This game proved effective not only in helping children learn the sizes of the numbers and organize them on a mental number line, but also in helping them learn to count, to identify printed numbers, and to learn the answers to simple addition problems. A version of the game involving a 10 × 10 matrix helped slightly older children learn about the numbers 1–100.

This merging of scientific research and educational application is a highly promising direction not only for improving mathematics instruction but also for improving instruction in reading, writing, science, and other areas. Insights from research are already being applied to these areas to some extent, but much greater benefits are within reach. The combination of investigators conducting research directly relevant to instruction and educators applying the lessons of the research in classrooms can make this promise a reality.

## REFERENCES

Siegler, R. S. (1976). *Three aspects of cognitive development*. New York: Elsevier.
Siegler, R. S. (1991). *Children's thinking*. Englewood Cliffs: Prentice-Hall.
Siegler, R. S. (1996). *Emerging minds: The process of change in children's thinking*. New York: Oxford.