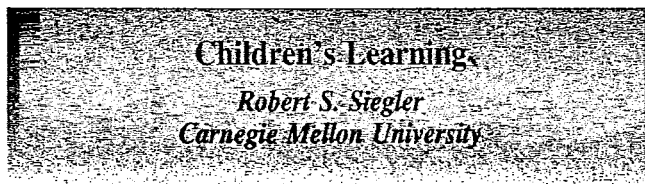


- Siegler, R. S. (2005). Children's Learning. *American Psychologist*, *60*, 769-778.
- Shrager, J., & Siegler, R. S. (1998). SCADS: A model of children's strategy choices and strategy discoveries. *Psychological Science*, *9*, 405-410.
- Siegler, R. S. (1976). Three aspects of cognitive development. *Cognitive Psychology*, *8*, 481-520.
- Siegler, R. S. (1981). Developmental sequences within and between concepts. *Society for Research in Child Development Monographs*, *46*(2, Whole No. 189).
- Siegler, R. S. (1987). The perils of averaging data over strategies: An example from children's addition. *Journal of Experimental Psychology: General*, *116*, 250-264.
- Siegler, R. S. (1995). How does change occur: A microgenetic study of number conservation. *Cognitive Psychology*, *28*, 225-273.
- Siegler, R. S. (1996). *Emerging minds: The process of change in children's thinking*. New York: Oxford University Press.
- Siegler, R. S. (2002). Microgenetic studies of self-explanations. In N. Granott & J. Parziale (Eds.), *Microdevelopment: Transition processes in development and learning* (pp. 31-58). New York: Cambridge University Press.
- Siegler, R. S. (in press). Microgenetic analyses of learning. In W. Damon (Series Ed.) & D. Kuhn & R. S. Siegler (Vol. Eds.), *Handbook of child psychology: Vol. 2: Cognition, perception, and language* (6th ed.). New York: Wiley.
- Siegler, R. S., & Araya, R. (2005). A computational model of conscious and unconscious strategy discovery. In R. V. Kail (Ed.), *Advances in child development and behavior* (Vol. 33, pp. 1-42). Oxford, England: Elsevier.
- Siegler, R. S., & Booth, J. L. (2004). Development of numerical estimation in young children. *Child Development*, *75*, 428-444.
- Siegler, R. S., & Crowley, K. (1991). The microgenetic method: A direct means for studying cognitive development. *American Psychologist*, *46*, 606-620.
- Siegler, R. S., & Crowley, K. (1994). Constraints on learning in nonprivileged domains. *Cognitive Psychology*, *27*, 194-227.
- Siegler, R. S., & Jenkins, E. A. (1989). *How children discover new strategies*. Hillsdale, NJ: Erlbaum.
- Siegler, R. S., & Lemaire, P. (1997). Older and younger adults' strategy choices in multiplication: Testing predictions of ASCM using the choice/no-choice method. *Journal of Experimental Psychology: General*, *126*, 71-92.
- Siegler, R. S., Liebert, D. E., & Liebert, R. M. (1973). Inhelder and Piaget's pendulum problem: Teaching preadolescents to act as scientists. *Developmental Psychology*, *9*, 97-101.
- Siegler, R. S., & Opfer, J. (2003). The development of numerical estimation: Evidence for multiple representations of numerical quantity. *Psychological Science*, *14*, 237-243.
- Siegler, R. S., & Shrager, J. (1984). Strategy choices in addition and subtraction: How do children know what to do? In C. Sophian (Ed.), *The origins of cognitive skills* (pp. 229-293). Hillsdale, NJ: Erlbaum.
- Siegler, R. S., & Stern, E. (1998). Conscious and unconscious strategy discoveries: A microgenetic analysis. *Journal of Experimental Psychology: General*, *127*, 377-397.



A new field of children's learning is emerging. This new field differs from the old in recognizing that children's learning includes active as well as passive mechanisms and qualitative as well as quantitative changes. Children's learning involves substantial variability of representations and strategies within individual children as well as across different children. The path of learning involves the introduction of new approaches as well as changes in the frequency of prior ones. The rate and the breadth of learning tend to occur at a human scale, intermediate between the extremes depicted by symbolic and connectionist models. Learning has many sources; one that

Editor's Note

Robert S. Siegler received the Award for Distinguished Scientific Contributions. Award winners are invited to deliver an award address at the APA's annual convention. A version of this award address was delivered at the 113th annual meeting, held August 18-21, 2005, in Washington, DC. Articles based on award addresses are reviewed, but they differ from unsolicited articles in that they are expressions of the winners' reflections on their work and their views of the field.

is particularly promising for educational purposes is self-explanations. Overall, contemporary analyses show that learning and development have a great deal in common.

Learning has always been a central part of childhood, but the study of learning has only sometimes been a central part of developmental psychology. Classic theorists such as Vygotsky, Dewey, Skinner, and Bandura highlighted the role of children's learning, and the subject was a major focus of developmental research through the 1960s. With the demise of learning theories, however, the study of children's learning drastically declined, to the point where a review of the field in the 1983 *Handbook of Child Psychology* noted that "by the mid-1970s, articles on children's learning dwindled to a fraction of the number that had been published in the previous decade, and by 1980 it was necessary to search with diligence to uncover any articles at all" (Stevenson, 1983, p. 213). There were good reasons for this decreased emphasis on children's learning, including both the deficiencies of the learning theory approaches themselves and the appeal of alternative theories of development, such as Piaget's, that did not emphasize learning. However, the near disappearance of the area left a hole in developmental psychology's depiction of child development.

The great theoretical questions sometimes leave the spotlight, but they always return. A new and vigorous field of children's learning has arisen and is generating intriguing empirical discoveries and theoretical insights. In this article, I sketch this emerging field and some of the discoveries and insights that it has already yielded.

Death and Rebirth of the Field of Children's Learning

The withering of the area of children's learning after about 1970 had a number of sources. One was the basic depiction of children as passive, inactive organisms; this flew in the face of discoveries about the active and constructive nature of much of cognition that was evident not only in Piaget's studies but also in studies of adult information processing (e.g., Bransford & Johnson, 1973). A second major problem was that the tasks studied by learning theorists had little ecological validity; they tended to be simple nonverbal problems that bore, at best, an abstract resemblance to the tasks that children encounter in the everyday environment. A third serious problem was the lack of dramatic and compelling discoveries emerging from the field.

The new field of children's learning is quite different in all three respects. Children are recognized as using both active and passive learning mechanisms. They actively strive to construct strategies to solve novel problems (Siegler & Jenkins, 1989) and reflect on their successes and failures (Kuhn & Franklin, in press), but they also benefit from statistical learning, associative learning, pattern recognition, and other passive mechanisms (Saffran, in

press). Contemporary models often depict how active and passive mechanisms work together to produce a single acquisition. For example, Shrager and Siegler's (1998) and Siegler and Araya's (2005) computer simulations have depicted mathematics learning as reflecting both associative mechanisms, which link strategies to the speed and accuracy that they produce on various types of problems, and metacognitive mechanisms, which are important for generating new strategies. The passive and active mechanisms within the models interact to produce learning. Growing associative strength frees working-memory capacity and thus makes possible generation of new strategies; the new strategies, in turn, influence subsequent formation of associations.

A second distinguishing characteristic of the new field of children's learning is that the tasks that receive the most attention tend to be taken from the everyday environment: reaching; locomoting up and down ramps; finding hidden objects; solving math and science problems; forming biological, psychological, numerical, and spatial concepts; and so on.

Probably most important, the new field has yielded a number of intriguing and often counterintuitive findings—for example, that new strategies are often discovered when existing strategies are yielding successful performance and that new strategies are often used only sporadically at first, even when children can explain the advantages of the new approaches (Karmiloff-Smith, 1979; Siegler & Jenkins, 1989). These and other findings have emerged consistently across a wide range of domains and age groups and in the studies of investigators of varied theoretical persuasions—Piagetian, information processing, sociocultural, and dynamic systems among them.

Progress in understanding children's learning has been greatly enhanced by the advent of *microgenetic* methods (Miller & Coyle, 1999; Siegler, in press). Such methods have three main properties: Observations span the period of rapidly changing competence; within this period, the density of observations is high relative to the rate of change of the phenomena of interest; and observations are intensively analyzed, with the goal of inferring the representations and processes that gave rise to the learning. The high density of observations is probably the essential feature for understanding the learning process. Learning tends to follow irregular paths involving regressions as well as progress, short-lived transitional approaches, inconsistent patterns of generalization, and other complexities. Because of this complexity, the only way to determine how children learn is to follow them closely while they are learning. Microgenetic methods often examine the acquisition process on a trial-by-trial basis, which allows the fine level of detail needed to identify exactly when children first use new strategies, the events that led up to the discovery, how the discovery was generalized, and other specifics of learning.

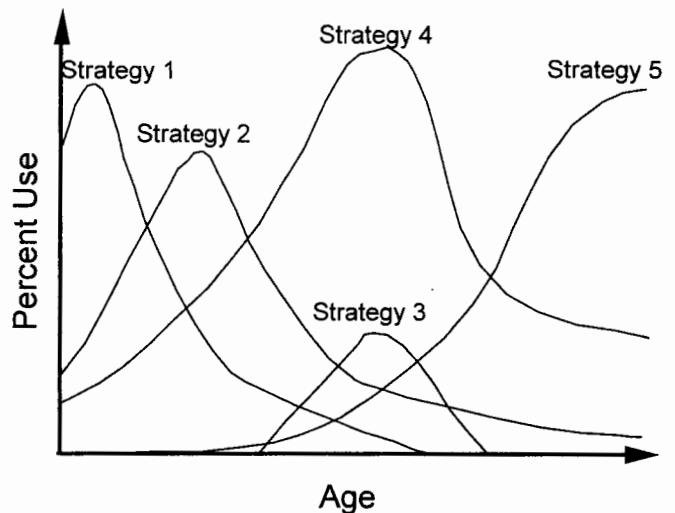
The exact methods used to assess children's strategies and representations vary with the ages of the children being studied. Trial-by-trial assessments for children four years old and younger have usually relied entirely on videotaped records of overt behavior. Such data have been used to study infants' motor development, toddlers' problem solving, and preschoolers' counting, memory, and attentional strategies. Assessments for children five years old and older have usually relied on a combination of videotaped recordings of ongoing behavior and immediately retrospective self-reports of "how I solved that problem." The overt behavior is the basis of classification on trials on which it provides unambiguous evidence of which strategy or representation was used; the verbal reports are used on trials on which overt behavior is absent or ambiguous. This combination yields reliable and valid assessments of strategy use in a great many situations, including arithmetic, spelling, time telling, serial recall, and scientific reasoning (Siegler, in press). In particular, verbal reports allow accurate and nonreactive identification of strategy use on trials on which overt behavior is absent or ambiguous, and they converge with (and help explain) data from other measures, such as solution times and error patterns (McGilly & Siegler, 1990; Robinson, 2001; Siegler, 1987).

Because of the detail they provide about changing competence, microgenetic data have stimulated the progress of a number of developmental theories that emphasize learning. These include dynamic systems (Smith, Thelen, Titzer, & McLin, 1999), sociocultural (Granott, 2002), and overlapping waves (Siegler, 1996) approaches. The last of these can be used to illustrate the kinds of theories of children's learning that are emerging.

The basic assumption of *overlapping waves* theory is that both learning and development are processes of variability, choice, and change. As illustrated in Figure 1, children are viewed as typically knowing and using a variety of strategies for solving a given problem at a given time. With age and experience, some strategies become less frequent (Strategy 1), others become more frequent (Strategy 5), and some become more frequent and then less frequent (Strategy 2). New strategies are discovered (Strategies 3 and 5), and some older strategies cease to be used (Strategy 1). Sometimes all of these phenomena can be seen within a single study (e.g., Siegler, 1995).

One advantage of overlapping waves theory is that it provides a means of integrating qualitative and quantitative aspects of learning within the same framework. The approach recognizes that children generate qualitatively different strategies and concepts; it also recognizes that much of development results from quantitative shifts in the frequency of use of strategies and concepts, the adaptiveness of choices among them, and the efficiency of their use. Children's learning clearly involves both qualitative and quantitative changes; there is no reason for the field of

Figure 1
The Overlapping Waves Model



children's learning to focus on one to the exclusion of the other.

Overlapping waves theory also makes several assumptions that are not evident in Figure 1. One such assumption is that from early in learning, children usually choose adaptively among strategies; that is, they choose strategies that fit the demands of problems and circumstances and that yield desirable combinations of speed and accuracy, given the strategies and available knowledge that children possess. Children may not know any strategies that yield accurate and fast performance on a given task, but they usually choose adaptively among the strategies they do know. Strategy choices sometimes become even more adaptive with experience in using the strategies. For example, from the beginning of their experience with ramps, toddlers adjust their descent strategies to the steepness of the particular ramp (Adolph, 1997). They use quicker but riskier means of locomotion (e.g., walking) on shallower ramps and slower but surer strategies (e.g., lying down on the ramp and sliding feet first) on steeper ones. With age and locomotor experience, infants' descent strategies become even more finely calibrated to a ramp's slope (Adolph, 1997). However, as with many types of learning, the improvement is linked to specific contexts; the increasingly adaptive strategy choices that are acquired in the period when crawling is the toddlers' predominant mode of locomotion need to be reacquired when walking becomes the predominant mode.

Overlapping waves theory suggests that learning can be profitably analyzed along five dimensions: path, rate, breadth, source, and variability. The *path of learning* is the sequence of knowledge states, representations, or predominant behaviors that children use while gaining competence.

The *rate of learning* concerns the amount of time or experience needed for a given acquisition. The *breadth of learning* involves the range of problems and contexts to which approaches are generalized. The *source of learning* involves the causes that set learning in motion. The *variability of learning* refers to the changing set of strategies used by individual children as well as to individual differences in the other dimensions. The rest of this article uses these five dimensions of cognitive change as a framework for organizing findings that are emerging from contemporary studies of children's learning.

Variability of Learning

Perhaps the most consistent phenomenon that has emerged in contemporary studies of children's learning is the great variability that exists within the thinking of each individual. It has long been known that different people use different approaches; however, trial-by-trial assessments have also revealed that the same person often thinks about the same type of problem in multiple ways, especially during learning experiences. One particularly striking example came from a study of how fifth graders and adults learn scientific experimentation skills; participants changed their minds an average of 14 times about whether a specific variable exercised a causal influence (Schauble, 1996). Substantial cognitive variability is present even within a single person solving a single problem on two occasions close in time. For example, when presented with the same single-digit addition problems on two occasions within the same week, preschoolers switched strategies on one third of the problems; the same was true for second graders asked to tell time on an analog clock (Siegler & McGilly, 1989; Siegler & Shrager, 1984). The cognitive variability cannot be explained entirely in terms of learning. In these and other studies in which children used different strategies on identical problems on two occasions close in time, 40%–45% of the changes were from more advanced to less advanced approaches rather than from less advanced to more advanced ones (Siegler, in press). The overall trend of learning is toward greater use of more advanced approaches, but many regressions occur along the way.

Such within-subject variability has been found in the strategies of children of a wide range of ages in a wide range of contexts: infants' locomotion (Adolph, 1997), toddlers' tool use (Chen & Siegler, 2000), preschoolers' selective attention and categorical recall (Coyle & Bjorklund, 1997; Miller & Aloise-Young, 1995), school-age children's and adults' mathematical and scientific reasoning strategies (Alibali, 1999; Schauble, 1996), and many others. The variability is not limited to use of one strategy on one trial and another strategy on another; it is also seen within a single trial. For example, children frequently express one strategy in speech and another in gesture on the same trial (Church, 1999). They also often generate multiple explana-

tions for the same outcome, some of them contradictory (Siegler, 1995).

This variable strategy use might be viewed as a mere piece of minutia—necessary for accurate description but of no broader importance. However, high initial variability often has been found to be predictive of subsequent learning, and it appears to be causally related to it. The number of different strategies used on a pretest is positively related to subsequent learning by children and adults on number conservation, serial-recall, and gear-rotation tasks (Coyle & Bjorklund, 1997; Perry & Elder, 1997; Siegler, 1995). The same relation is present within a single trial; use of two or more visibly different strategies, different explanations, or gesture–speech mismatches on a trial is positively related to subsequent learning (Siegler, in press). Moreover, experimental conditions that promote learning frequently lead to heightened variability of strategies before they lead to greater accuracy or shorter solution times (Siegler, 2002).

Several explanations have been advanced for the positive relation of within-child variability to subsequent learning. Dynamic systems theories postulate that systems change only after becoming unstable; increased strategic variability is a form of instability, and learning is a form of change (Thelen & Corbetta, 2002). Another hypothesis, advanced to account for the positive relation of gesture–speech mismatches to learning, is that simultaneous activation of competing representations leads to extension of the more advanced representation to both modalities (Goldin-Meadow & Alibali, 2002). A third hypothesis, generated within overlapping waves theory, is that new strategies are often constructed from components of existing approaches; such a construction process is more likely when both relevant strategies have been used recently and, thus, are relatively active (Siegler & Araya, 2005).

Path of Learning

Piagetian, theory-theory, and some information-processing approaches propose that children progress through regular developmental sequences on their way to mastery of many concepts and problem-solving skills. Young children display a rudimentary understanding, somewhat older children a somewhat more advanced understanding, yet older children a yet more advanced understanding, and so on.

The *developmental sequences* construct was formulated to account for age-related change. However, children generate highly similar sequences of qualitatively distinct approaches over much shorter time periods in the context of learning experiments. This has been documented for sequences of balance-scale rules (Siegler & Chen, 1998), scientific experimentation strategies (Kuhn, Garcia-Mila, Zohar, & Anderson, 1995), mathematical equality strategies (Goldin-Meadow & Alibali, 2002), representations of the *living things* concept (Opfer & Siegler, 2004), and numerous other problems.

The omnipresent within-child variability described in the previous section indicates that in learning as in development, the idea that children progress from one approach to a second approach to a third approach is too simple. However, a somewhat more complex version of the developmental-sequence idea remains valuable for understanding development and learning. Within this version, developmental sequences involve changing distributions of approaches rather than substitution of one approach for another; development and learning involve not only the type of qualitative change involved in traditional ideas about developmental sequences but also quantitative trends in the frequency of existing approaches.

The microgenetic designs used in contemporary studies of learning also have allowed discovery of short-lived transition strategies that were not evident in previous studies of age-related change that sampled changing competence less frequently. For example, when toddlers progress beyond their first 50 words and begin to acquire new words rapidly, they generate naming errors at a much higher rate than either before or after (Gershkoff-Stowe & Smith, 1997). Similarly, when presented with problems of the form $a + b - b$, second graders at first add and subtract the three numbers and later adopt an insight strategy: Just say the first number, because adding and subtracting the same number invariably leaves that number unchanged (Siegler & Stern, 1998). In between, there is a brief transition period during which children's solution times demonstrate that they are using the insight strategy (the times are too short for the children to have added and subtracted) but during which children continue to say that they added and subtracted; in other words, they have had the insight, but at an unconscious rather than a conscious level. This strategy is present only for three to five trials after children's solution times plunge below the level required to add and subtract. It is not surprising that this short-lived strategy was not discovered until learning was analyzed trial by trial.

Another way that recent studies of learning have enhanced understanding of the path of change is by casting doubt on whether hypothesized transition states occur. In one such study, Opfer and Siegler (2004) examined five-year-olds' understanding of the concept of living things. All three types of reasoning described by Piaget and other investigators—that all things are alive, that only animals are alive, and that animals and plants are alive—were seen in this study as well. Rather than progressing through these forms of reasoning in the order listed above, as had previously been hypothesized, children who began the study by categorizing all things as alive progressed directly to classifying both plants and animals as alive without going through the hypothesized intermediate state of classifying only animals as alive. Other children first classified only animals as alive and later classified plants as well as animals as alive, but there was no evidence that these children

had ever classified all things as alive. Thus, acquisition of the *living things* concept may involve two paths—each involving two approaches—rather than a single path involving three approaches.

This is not the only case in which different children have been found to learn via different pathways (e.g., Spencer, Vereijken, Diedrich, & Thelen, 2000). However, the more common finding is that different children progress via the same path. This can be seen in comparing the paths of learning of children of different ages who begin experiments using the same rules or strategies. In learning how to use tools to obtain a toy, both one-year-olds and two-year-olds typically progress through the same sequence of strategies (Chen & Siegler, 2000), as do four-year-olds and five-year-olds learning how to predict the actions of balance scales (Siegler & Chen, 1998) and 10-year-olds and adults learning to solve scientific reasoning problems (Kuhn et al., 1995). Older individuals tend to start farther along the path and to progress farther in response to the same experience, but the path usually is the same.

Another interesting discovery regarding the path of change has been that generation of new ways of thinking is constrained by conceptual understanding. Rather than learning being a process of trial and error, in which both inappropriate and appropriate strategies are attempted, learners frequently generate appropriate strategies without generating inappropriate ones (Siegler, 1995; Siegler & Jenkins, 1989). This is especially likely to occur when children possess goal sketches that indicate the objectives that appropriate strategies in a domain must meet (Siegler & Crowley, 1994; Thornton, 1999).

Detailed examination of the path of change also has yielded insights into the mechanisms that underlie learning. For example, Siegler and Svetina (2002) found that in solving matrix-completion problems, five- and six-year-olds rejected a dominant incorrect strategy well before they first generated a correct strategy. This was evident in the children's error patterns. After a prolonged period of generating the error yielded by the dominant incorrect approach on about 70% of trials, children chose approximately randomly among the six response alternatives for about a dozen trials. Both the previously dominant error and the correct alternative were chosen on about one sixth of trials during this period. Then the children discovered a correct approach, which they used on more than 80% of subsequent trials. This example, as well as similar findings on other tasks (Siegler, in press), indicates that rejection of existing approaches and generation of new ones are separate processes.

Rate of Learning

Debates about the rate of learning—for example, whether it is always gradual or can occur very rapidly, even within a single trial—were already prominent in the heyday of

learning theory. The controversy has continued to the present—for example, in the ongoing debate between connectionists, whose models typically learn very slowly, and symbolic modelers, whose models typically learn rapidly. For example, Newell's (1990) symbolic model learned new balance-scale rules in a single trial, whereas McClelland's (1995) connectionist model required thousands of trials to learn each new rule. Neither time grain is plausible; most children learn the rules modeled in these simulations at an in-between rate, ranging from a few trials to 20 or 30 (Siegler & Chen, 1998). This rate seems to be characteristic of human-scale acquisition of many new rules and strategies.

The recognition that learners often progress through a sequence of increasingly advanced ways of thinking has led to a conceptual distinction between two senses of the rate of learning: the amount of time or experience before the first use of a new approach and the amount of time-experience before learning reaches its asymptotic level. The first might be labeled the *rate of discovery*, the second the *rate of uptake*. The distinction is important, because the two rates are related loosely if at all. Some learning situations correspond to the stereotype of Archimedes brooding on a problem for a prolonged period and then exclaiming "Eureka" after entering the bath: Discovery of the new approach takes a long time, but uptake is almost instantaneous. For example, the six-year-olds in Siegler and Svetina (2002) took an average of 50 trials before they discovered a correct strategy for solving matrix-completion problems, but they used it consistently thereafter. In other cases, discovery is rapid but uptake is slow. In Siegler and Stern (1998), for example, second graders took only an average of 7 trials to discover an insight strategy for solving $a + b - b$ problems, but they did not use the strategy consistently even 100 trials later.

Experimental conditions also affect the two rates of learning differently. Some manipulations affect one but not the other; for example, in Siegler and Jenkins (1989), encountering challenge problems, which could be solved easily via a new strategy but not by previously available ones, did not affect the rate of discovery but did increase the rate of uptake. In other cases, a variable has opposite effects on the two rates: In Opfer and Siegler (2004), for example, one experimental condition led to slower discoveries but faster uptake than did the other two conditions.

Children's learning tends to differ from both connectionist and symbolic simulation models not only in the rate of discovery but also in the rate of uptake. In both types of simulation models, once advanced rules are discovered, they are used consistently (unless replaced by yet more advanced rules). In contrast, children's discovery of new rules is often only the beginning of learning. The rate of uptake typically is slow even when identical problems are presented. For example, in Siegler (1995), among those

beginning conservers who relied on the type of transformation to solve a number-conservation problem, only 43% again relied on the type of transformation when the identical problem was presented two sessions later. The slow uptake occurs even when children can explain why the new approach is superior (Siegler & Jenkins, 1989). A variety of factors influence the rate of uptake—for example, the rate tends to be faster for older children than for younger ones and faster for new strategies that offer large advantages in accuracy than for new strategies that have smaller advantages—but in most cases, the uptake of new ways of thinking is quite slow (Siegler, in press).

Breadth of Learning

Many educators and psychologists interested in education have lamented the narrowness and lack of transfer of children's learning (e.g., Bransford, Brown, & Cocking, 1999). Much less has been written, however, about the fact that children's learning also tends to be far from literal. One reason for the emphasis on the lack of transfer may be a tendency to define "transfer problems" as tasks on which useful, known strategies are rarely applied and to view tasks on which useful strategies are quickly extended to novel problems as not requiring transfer. Viewed more dispassionately, just as there seems to be a human-scale *rate* of learning, there also seems to be a human-scale *breadth* of learning—broader than the exact context in which the new approach was learned but narrower than the full set of contexts where it could be useful.

To arrive at the ideal breadth of learning, children must not only generalize the new approach to the full range of situations in which it applies, they must also *not* generalize the new approach to situations in which it does not apply. The challenge that this presents can be seen in findings regarding generalization of new strategies for solving mathematical equality problems of the form $A + B + C = ____ + C$. On the one hand, many third and fourth graders who learn to solve this problem fail to transfer their new understanding of the equal sign to structurally parallel $A \times B \times C = ____ \times C$ problems (Alibali, 1999). On the other hand, many children of this age who learn to solve $A + B + C = ____ + C$ problems correctly by adding $A + B$ then go on to inappropriately generalize that solution strategy to problems such as $A + B + C = ____ + D$, where it yields incorrect answers (Siegler, 2002). The 9- and 10-year-olds' difficulty in underextending their strategy in some situations and overextending it in others closely resembles 2-year-olds' tendency to underextend and overextend the same word (Bowerman, 1982). As with many aspects of learning, the same types of difficulties arise at different ages, though older children tend to overcome the difficulties more quickly (Siegler, in press).

Although generalizing appropriately poses large challenges, children sometimes establish the ideal breadth of

learning quite rapidly. One area in which this occurs is learning how to design scientific experiments that separate the contributions of different variables. Children who have learned to design such experiments in one area often extend their knowledge appropriately to other areas without any additional instruction (Chen & Klahr, 1999; Kuhn et al., 1995). In general, the breadth of learning tends to be greatest when new approaches yield dramatic improvements in accuracy. The breadth also tends to be greater when the new approach is applicable to all problems presented during learning than when the strategy is only applicable to some of the problems (Siegler & Stern, 1998).

Sources of Learning

At times, efforts to solve problems produce learning even in the absence of feedback or instruction. This has been seen for theory-of-mind inferences, scientific reasoning, analogical reasoning, memory strategies, map drawing, the game of 20 questions, and rediscovery of the decimal system following brain injury (Siegler, in press).

Feedback generally promotes learning beyond the level that occurs through problem solving in the absence of feedback, but contrary to the usual depiction, children often generate new strategies even when existing strategies are yielding correct performance—and, therefore, positive feedback—on the immediately preceding problems (Karmiloff-Smith, 1979; Siegler & Jenkins, 1989). Necessity sometimes is the mother of invention, but inventions also arise without external necessity.

One source of learning that has received a great deal of recent attention is self-explanation—attempts to explain for oneself the causes of events. Children who seek causal understanding of a domain both learn and remember better than do peers who do not seek such understanding. This finding has led to the question of whether prompting randomly chosen children to seek causal understanding would improve their learning as well.

The answer is yes. On a wide range of tasks, asking children to explain why observed events occurred or why the experimenter said that a given answer was correct promotes greater learning than does receiving feedback, reading the textbook twice, or spending more time on the task (Aleven & Koedinger, 2002; Chi, de Leeuw, Chiu, & Lavancher, 1994). The problems on which this self-explanation effect has been found include number conservation, mathematical equality, map drawing, geometry, balance scales, and understanding the functioning of the cardiac system. Moreover, asking learners to explain both why correct answers are correct and why incorrect answers are incorrect leads to even greater learning than does only asking why correct answers are correct (Siegler, 2002). Prompting such self-explanations has an especially large effect on problems that are relatively far from those on which learning originally occurred (Alibali, 1999; Siegler, 2002), an

effect that suggests that such questions lead to deeper understanding of the causal and structural relations in the domain than does feedback alone.

Explanatory activity enhances learning through several mechanisms. At a general level, the effect seems to arise through increased depth of processing. More specifically, explanatory activity increases learners' likelihood of generating any explanation for their observations, and it also motivates them to probe deeper when they do seek an explanation. For example, when third and fourth graders were presented with mathematical equality problems of the form $A + B + C = \text{_____} + C$ and given feedback on the correctness of their answers, children who were also asked to explain both why correct answers were right and why incorrect answers were wrong generated more explanations and deeper ones than did children who were either asked to explain correct answers or to explain their own answers (Siegler, 2002). One sign of the deeper processing was that the solution times of the children who were asked to explain both correct and incorrect answers rose more (from an average of 11 s to 25 s) over the first three trials than did the times of children in the other two groups. Then the answers of the children who were asked to explain correct and incorrect answers returned to the original 10–11 s, showing that there was nothing inherently more time-consuming about the new strategy. Children who explained both types of answers also more often solved the problems not by the simplest strategy of adding $A + B$ but, instead, by more conceptually advanced approaches, such as figuring out what number to add to the right side so that the values on the left and right sides would be the same. This strategy, unlike adding $A + B$, could be extended to transfer problems such as $A + B + C = \text{_____} + D$.

Another mechanism that may contribute to the effectiveness of explaining why incorrect answers are incorrect is weakening of the associative strength of flawed strategies. The frequency of the incorrect strategy that initially predominated in Siegler (2002)—adding $A + B + C$ —decreased much more rapidly in the group that was asked to explain why that strategy was wrong as well as why a different strategy was right. Given the prolonged competition that characterizes uptake of most strategies, experiences that weaken older, nonoptimal strategies should generally enhance the uptake of new, superior alternatives.

One reason why requests to explain observations and statements by teachers and textbooks is of such interest is its potential for improving classroom instruction. Encouragement of self-explanations requires no technology or funding to use, can be applied to virtually any subject, and has already been shown to improve the learning of persons from kindergarten age through adulthood. Moreover, such questions can be used to supplement almost any curriculum. Thus, encouraging self-explanations seems very promising as a means for improving education.

Relations Between Learning and Development

The relation of learning to development has been of interest throughout the history of developmental psychology. Classical theorists adopted conflicting stances regarding it. Vygotsky (1934/1962) and Werner (1948) viewed short-term change as a miniature version of long-term change, with the same sequence of qualitatively different stages and the same underlying processes. Learning theorists such as Kendler and Kendler (1962) also viewed the two as being driven by the same processes, though they portrayed both as being gradual and continuous rather than including qualitatively discrete stages. Piaget (1964) took a third stance; from his perspective, development and learning were dissimilar. Within this view, development involved the creation of new, qualitatively distinct structures, whereas learning just filled in specific content within the structures.

This issue has continued to be of great interest within the new field of children's learning. There seems to be a broad consensus that learning and development have a great deal in common, both at the level of behavior and at the level of underlying mechanisms. This consensus includes exponents of dynamic systems theories (e.g., Thelen & Corbetta, 2002), neo-Piagetian theories (Granott, 2002), and information-processing theories (Siegler, in press). For example, Thelen and Corbetta (2002) stated, "We study microdevelopment because we believe that the processes that cause change in a matter of minutes or hours are the same as those working over months or years" (p. 60).

The type of evidence that has led to this conclusion is exemplified by a study of class inclusion that combined cross-sectional methods for studying age-related change with microgenetic methods for studying learning (Siegler & Svetina, 2002). In the cross-sectional portion of the study, six-, seven-, and eight-year-olds were presented with matrix-completion and conservation problems within a single session. In the microgenetic portion, a randomly selected half of the six-year-olds who participated in the cross-sectional portion were then presented with four sessions of feedback and self-explanation questions on matrix-completion problems. Two months later, they, as well as the six-year-olds who were not presented with these learning sessions, were presented with a posttest on matrix completion and conservation.

A measure of the global amount of learning produced by the four learning sessions—the pretest-to-posttest increase in percentage of correct answers—was comparable to the increase on the same measure between six- and seven-year-olds in the cross-sectional part of the study. This allowed a test of whether the detailed patterns of change with age and with learning were also comparable.

Examination of 11 measures of performance indicated that the changes were indeed highly similar. On 5 of the 11 measures, significant improvements occurred with both

age and participation in the four learning sessions; on another 5 measures, no significant improvements were apparent with either age or participation in the learning sessions. The specificity of the matches was often striking. For example, the number of answers that were correct on the size dimension showed significant improvement in both comparisons, but the number of explanations that cited size did not show significant changes in either. At both ages and at both pretest and posttest, the same characteristic error was present; in all cases, it accounted for about 70% of the total errors (vs. 30% for the other four errors combined). Improvements following the learning sessions also were extremely stable over time and showed generalization to the conservation tasks; such stability and generalization are attributes that Piaget viewed as defining characteristics of development—and not of learning.

Findings like those of Siegler and Svetina (2002) indicate that at least some types of learning are highly similar to the age-related changes described by Piaget and other developmental theorists. Indeed, much of the rebirth of the field is attributable to insights from the study of age-related change being incorporated into the study of children's learning. This has created a distinctively developmental approach to learning, one that emphasizes both qualitative and quantitative change. Understanding of children's learning and understanding of child development more generally are the richer for it.

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References

- Adolph, K. E. (1997). Learning in the development of infant locomotion. *Monographs of the Society for Research in Child Development*, 62(3, Serial No. 251).
- Aleven, V. A. W. M. M., & Koedinger, K. R. (2002). An effective metacognitive strategy: Learning by doing and explaining with a computer-based cognitive tutor. *Cognitive Science*, 26, 147–179.
- Alibali, M. W. (1999). How children change their minds: Strategy change can be gradual or abrupt. *Developmental Psychology*, 35, 127–145.
- Bowerman, M. (1982). Starting to talk worse: Clues to language acquisition from children's late speech errors. In S. Strauss (Ed.), *U-shaped behavioral growth* (pp. 101–145). New York: Academic Press.

- Bransford, J. D., Brown, A. L., & Cocking, R. R. (Eds.) (1999). *How people learn: Brain, mind, experience, and school*. Washington, DC: National Academies Press.
- Bransford, J. D., & Johnson, M. K. (1973). Considerations of some problems of comprehension. In W. G. Chase (Ed.), *Visual information processing* (pp. 383–438). New York: Academic Press.
- Chen, Z., & Klahr, D. (1999). All other things being equal: Children's acquisition of the control of variables strategy. *Child Development, 70*, 1098–1120.
- Chen, Z., & Siegler, R. S. (2000). Across the great divide: Bridging the gap between understanding of toddlers' and older children's thinking. *Monographs of the Society for Research in Child Development, 65*(2, Whole No. 261).
- Chi, M. T. H., de Leeuw, N., Chiu, M.-H., & LaVancher, C. (1994). Eliciting self-explanations improves understanding. *Cognitive Science, 18*, 439–477.
- Church, R. B. (1999). Using gesture and speech to capture transitions in learning. *Cognitive Development, 14*, 313–342.
- Coyle, T. R., & Bjorklund, D. F. (1997). Age differences in, and consequences of, multiple- and variable-strategy use on a multiple sort-recall task. *Developmental Psychology, 33*, 372–380.
- Gershkoff-Stowe, L., & Smith, L. B. (1997). A curvilinear trend in naming errors as a function of early vocabulary growth. *Cognitive Psychology, 34*, 37–71.
- Goldin-Meadow, S., & Alibali, M. W. (2002). Looking at the hands through time: A microgenetic perspective on learning and instruction. In N. Granott & J. Parziale (Eds.), *Microdevelopment: Transition processes in development and learning* (pp. 80–105). Cambridge, England: Cambridge University Press.
- Granott, N. (2002). How microdevelopment creates macrodevelopment: Reiterated sequences, backward transitions, and the zone of current development. In N. Granott & J. Parziale (Eds.), *Microdevelopment: Transition processes in development and learning* (pp. 213–242). Cambridge, England: Cambridge University Press.
- Karmiloff-Smith, A. (1979). Micro- and macrodevelopmental changes in language acquisition and other representational systems. *Cognitive Science, 3*, 91–118.
- Kendler, H. H., & Kendler, T. S. (1962). Vertical and horizontal processes in problem solving. *Psychological Review, 69*, 1–16.
- Kuhn, D., & Franklin, S. (in press). The second decade: What develops (and how)? In W. Damon & R. M. Lerner (Series Eds.) & D. Kuhn & R. S. Siegler (Vol. Eds.) *Handbook of child psychology: Vol. 2: Cognition, perception, and language* (6th ed.). Hoboken, NJ: Wiley.
- Kuhn, D., Garcia-Mila, M., Zohar, A., & Anderson, C. (1995). Strategies of knowledge acquisition. *Monographs of the Society for Research in Child Development, 60*(4, Serial No. 245).
- McClelland, J. L. (1995). A connectionist perspective on knowledge and development. In T. J. Simon & G. S. Halford (Eds.), *Developing cognitive competence: New approaches to process modeling* (pp. 157–204). Hillsdale, NJ: Erlbaum.
- McGilly, K., & Siegler, R. S. (1990). The influence of encoding and strategic knowledge on children's choices among serial recall strategies. *Developmental Psychology, 26*, 931–941.
- Miller, P. H., & Aloise-Young, P. A. (1995). Preschoolers' strategic behavior and performance on a same-different task. *Journal of Experimental Child Psychology, 60*, 284–303.
- Miller, P. H., & Coyle, T. R. (1999). Developmental change: Lessons from microgenesis. In E. K. Scholnick, K. Nelson, S. A. Gelman, & P. H. Miller (Eds.), *Conceptual development: Piaget's legacy* (pp. 209–239). Mahwah, NJ: Erlbaum.
- Newell, A. (1990). *Unified theories of cognition*. Cambridge, MA: Harvard University Press.
- Opfer, J. E., & Siegler, R. S. (2004). Revisiting preschoolers' *living things* concept: A microgenetic analysis of conceptual change in basic biology. *Cognitive Psychology, 49*, 301–332.
- Perry, M., & Elder, A. D. (1997). Knowledge in transition: Adults' developing understanding of a principle of physical causality. *Cognitive Development, 12*, 131–157.
- Piaget, J. (1964). Development and learning. In T. Ripple & V. Rockcastle (Eds.), *Piaget rediscovered* (pp. 7–19). Ithaca, NY: Cornell University Press.

- Robinson, K. M. (2001). The validity of verbal reports in children's subtraction. *Journal of Educational Psychology, 93*, 211-222.
- Saffran, J. (in press). The infant's auditory world: Hearing, speech, and the beginnings of language. In W. Damon & R. M. Lerner (Series Eds.) & D. Kuhn & R. S. Siegler (Vol. Eds.), *Handbook of child psychology: Vol. 2: Cognition, perception, and language* (6th ed.). Hoboken, NJ: Wiley.
- Schauble, L. (1996). The development of scientific reasoning in knowledge-rich contexts. *Developmental Psychology, 32*, 102-119.
- Shrager, J., & Siegler, R. S. (1998). SCADS: A model of children's strategy choices and strategy discoveries. *Psychological Science, 9*, 405-410.
- Siegler, R. S. (1987). The perils of averaging data over strategies: An example from children's addition. *Journal of Experimental Psychology: General, 116*, 250-264.
- Siegler, R. S. (1995). How does change occur: A microgenetic study of number conservation. *Cognitive Psychology, 28*, 225-273.
- Siegler, R. S. (1996). *Emerging minds: The process of change in children's thinking*. New York: Oxford University Press.
- Siegler, R. S. (2002). Microgenetic studies of self-explanation. In N. Granott & J. Parziale (Eds.), *Microdevelopment: Transition processes in development and learning* (pp. 31-58). Cambridge, England: Cambridge University Press.
- Siegler, R. S. (in press). Microgenetic analyses of learning. In W. Damon & R. M. Lerner (Series Eds.) & D. Kuhn & R. S. Siegler (Vol. Eds.), *Handbook of child psychology: Vol. 2: Cognition, perception, and language* (6th ed.). Hoboken, NJ: Wiley.
- Siegler, R. S., & Araya, R. (2005). A computational model of unconscious and conscious strategy discovery. In R. Kail (Ed.), *Advances in child development* (Vol. 33, pp. 1-42). Oxford, England: Elsevier.
- Siegler, R. S., & Chen, Z. (1998). Developmental differences in rule learning: A microgenetic analysis. *Cognitive Psychology, 36*, 273-310.
- Siegler, R. S., & Crowley, K. (1994). Constraints on learning in nonprivileged domains. *Cognitive Psychology, 27*, 194-226.
- Siegler, R. S., & Jenkins, E. A. (1989). *How children discover new strategies*. Hillsdale, NJ: Erlbaum.
- Siegler, R. S., & McGilly, K. (1989). Strategy choices in children's time-telling. In I. Levin & D. Zakay (Eds.), *Time and human cognition: A life span perspective* (pp. 185-218). Amsterdam: Elsevier Science.
- Siegler, R. S., & Shrager, J. (1984). Strategy choices in addition and subtraction: How do children know what to do? In C. Sophian (Ed.), *Origins of cognitive skills* (pp. 229-293). Hillsdale, NJ: Erlbaum.
- Siegler, R. S., & Stern, E. (1998). A microgenetic analysis of conscious and unconscious strategy discoveries. *Journal of Experimental Psychology: General, 127*, 377-397.
- Siegler, R. S., & Svetina, M. (2002). A microgenetic/cross-sectional study of matrix completion: Comparing short-term and long-term change. *Child Development, 73*, 793-809.
- Smith, L. B., Thelen, E., Titzer, R., & McLin, D. (1999). Knowing in the context of acting: The task dynamics of the A-not-B error. *Psychological Review, 106*, 235-260.
- Spencer, J. P., Vereijken, B., Diedrich, F. J., & Thelen, E. (2000). Posture and the emergence of manual skills. *Developmental Science, 3*, 216-233.
- Stevenson, H. W. (1983). How children learn: The quest for a theory. In P. H. Mussen (Series Ed.) & W. Kessen (Vol. Ed.), *Handbook of child psychology: Vol. 1: History, theory and methods* (pp. 213-236). New York: Wiley.
- Thelen, E., & Corbetta, D. (2002). Microdevelopment and dynamic systems: Applications to infant motor development. In N. Granott & J. Parziale (Eds.), *Microdevelopment: Transition processes in development and learning* (pp. 59-79). Cambridge, England: Cambridge University Press.
- Thornton, S. (1999). Creating the conditions for cognitive change: The interaction between task structures and specific strategies. *Child Development, 70*, 588-603.
- Vygotsky, L. S. (1962). *Thought and language* (E. Hanfmann & G. Vakar, Eds. & Trans.). New York: Wiley. (Original work published 1934)
- Werner, H. (1948). *Comparative psychology of mental development*. New York: International Universities Press.