The Microgenetic Method

A Direct Means for Studying Cognitive Development

Robert S. Siegler and Kevin Crowley Carnegie Mellon University

Progress in understanding cognitive developmental change mechanisms requires methods that yield detailed data about particular changes. The microgenetic method is an approach that can yield such data. It involves (a) observations of individual children throughout the period of the change, (b) a high density of observations relative to the rate of change within that period, and (c) intensive trial-by-trial analyses intended to infer the processes that gave rise to the change. This approach can illuminate both qualitative and quantitative aspects of change, indicate the conditions under which changes occur, and yield otherwise unobtainable information about short-lived transition strategies. The cost in time and effort of such studies is often high, but the value of the information about change can more than justify the cost.

The essence of development is change. However, determining how change occurs is very difficult. Historically, this difficulty has limited both theoretical and empirical progress in understanding cognitive development. As Flavell (1984) commented,

Serious theorizing about basic mechanisms of cognitive growth has actually never been a popular pastime, now or in the past. It is rare indeed to encounter a substantive treatment of the problem in the annual flood of articles, chapters, and books on cognitive development. (p. 189)

In the past few years, however, considerable progress has been evident. Deepening recognition of the importance of understanding change has led to increasingly precise theorizing about the mechanisms that produce it. This emphasis is reflected in the titles of several recent edited volumes: Mechanisms of Cognitive Development (Sternberg, 1984), Mechanisms of Language Acquisition (MacWhinney, 1987), and Transition Mechanisms in Child Development: The Longitudinal Perspective (de Ribaupierre, 1989). Descriptions of a number of the most promising current models of cognitive developmental change mechanisms and an analysis of what they share in common is provided in Siegler (1989b).

One reason why progress in understanding these mechanisms has been so long in coming has been the difficulty of devising effective methods for studying the topic. As Appelbaum and McCall (1983) noted, “In contrast to other specialties, the study of development is the study of change . . . . But developmental psychology has often not been truly developmental, and therefore it has not seriously faced the methodological issues unique to its definitional purpose” (p. 415).

Again, however, movement is apparent. The challenges of studying change are increasingly being accepted. This trend is not unrelated to the theoretical progress being made in understanding basic mechanisms. Studies that examine changes while they are occurring suggest ideas about the mechanisms that produce the changes and also provide data against which to evaluate the plausibility and power of potential mechanisms. The theoretical progress, in turn, creates greater demand for revealing methods that can resolve points of disagreement among alternative models and that can indicate directions in which models need to be extended.

The main purposes of this article are to describe a method that seems particularly well suited to studying change, to review the progress that has been made using it, and to advocate its increased use. Different investigators have used different labels, but the most common is the microgenetic method.

The Microgenetic Method

Three key properties define the microgenetic approach: (a) Observations span the entire period from the beginning of the change to the time at which it reaches a relatively stable state. (b) The density of observations is high relative to the rate of change of the phenomenon. (c) Observed behavior is subjected to intensive trial-by-trial analysis, with the goal of inferring the processes that give rise to both quantitative and qualitative aspects of change. The research was supported by grants from the Spencer Foundation, the McDonnell Foundation, the Mellon Foundation, and the National Institutes of Health (Grant HD19011), as well as by a National Institute of Mental Health predoctoral fellowship.

Thanks to David Klahr and Leona Schauble for their helpful readings of an earlier draft of the article and to Mark Ashcraft, Don Foss, and an anonymous reviewer for their constructive reviews.

Correspondence concerning this article should be addressed to Robert S. Siegler, Psychology Department, Carnegie Mellon University, Pittsburgh, PA 15213.

June 1991 • American Psychologist

Copyright 1991 by the American Psychological Association, Inc. 0003-066X/91/$2.00
Vol. 48, No. 4, 606-620
rationale underlying the approach and its history and uses to date are examined in this section.

**Rationale**

Most developmental methods only indirectly assess change. They are more like snapshots than movies. This criticism has often been leveled at cross-sectional designs, but it applies equally to most longitudinal approaches. Observing a given child at ages 6, 8, 10, and 12 tells us more about stability of individual differences than does observing different children of each age at a single point in time. However, ordinarily it tells us no more about the process that produced the changes.

The crucial variable is not whether the design is longitudinal, but rather is the density of observations during the period of change relative to the rate of change of the phenomenon. This can be illustrated by thinking of depictions of tornadoes or hurricanes descending on a town. Photographs of an area before and after a cataclysm allow appreciation of the extent of damage and often elicit a "wow" reaction. To comprehend the process that wreaked the damage, however, requires observation of the effects at much more frequent intervals. A movie is ideal, but even a sequence of still photos, taken before, after, and at frequent intervals during the storm, yields a much finer understanding of the change than do before-and-after shots. Especially important, observation and measurement of ongoing changes allows analysis of the relation between the damage being done and changes in cloud formations, barometric pressure, wind patterns, and other causal influences.

The situation is the same in trying to understand the less cataclysmic process of cognitive change. Suppose we wanted to study development of understanding of liquid quantity conservation. Suppose further that individual children took roughly one month to progress from thinking that the taller liquid column must contain more water, to being unsure, to realizing that simply pouring the water does not change its quantity. Examining understanding of liquid quantity conservation at ages five, six, seven, and eight would indicate how many children understood the concept at each age. It also might prove informative concerning their reasoning before they understood the importance of the transformation. However, regardless of whether the design was cross-sectional or longitudinal, such a study would reveal little about how the change occurred. The density of observations during the period of change would simply be too low relative to the rate of conservation acquisition.

Dense sampling of behaviors over time has an obvious cost in terms of time, effort, and money. This cost makes it essential that the period of intense sampling substantially coincide with the period during which the rate of change is relatively rapid. Ideally, the observations would begin shortly before the change began and would continue until a point of relative stability was reached.

With changes that are closely age linked, the combination of a relatively dense distribution of observations and a high degree of overlap between the period of ob-

servation and the period of rapid change allows much more direct observation of the process of change than is typical. For example, binocular depth perception (stereopsis) consistently emerges in infants between 12 and 24 weeks of age. This regularity led Shimojo, Bauer, O'Connell, and Held (1986) to test the stereo acuity of infants at 1-week intervals from ages 4 to 26 weeks. The study revealed that the developmental function for individual infants was much steeper than for the group as a whole. Typically, an infant moved in 1 or 2 weeks from extremely poor to asymptotic levels of stereo acuity. Only a dense distribution of observations that was well targeted to the period of change would have produced this information.

Most changes, particularly those occurring after infancy, are not so tightly bound to particular ages, though. For example, children typically acquire conservation of liquid quantity between ages six and nine, but the variability of the age of acquisition is measured in years rather than weeks. Under this circumstance, it is prohibitively expensive to observe at frequent intervals while awaiting the change.

The need for dense sampling, combined with the long period of time over which age-related changes typically occur, creates serious difficulties for observing ongoing cognitive growth. However, investigators using microgenetic methods have developed two strategies for meeting the challenge. One is to choose a task from the everyday environment, hypothesize the types of experiences that typically lead to changes in performance on it, and provide a higher concentration of such experiences than would otherwise occur. An alternative approach is to present a novel task and to observe children's changing understanding of it within a single session or over multiple sessions. Both of these approaches have proved capable of yielding high-quality data about how change occurs.

It might be objected that such studies involve examinations of change over minutes, days, weeks, or months, rather than years, and that they therefore address issues of learning but not those of development (see Liben, 1987). Several considerations lessen the force of this argument, however. Most important, having high-quality information about some types of change is surely better than not having such information about any type of change. As Werner (1948) hypothesized, there may be important commonalities underlying changes that occur on radically different time scales. The more precise the understanding that we can gain of any set of changes, the better our chance of theoretical progress in identifying such commonalities and thus of understanding long-term, as well as short- and medium-term, changes. In addition, distinguishing neatly between phenomena that reflect development and phenomena that reflect learning has proved no easier than distinguishing between phenomena that reflect genetics and those that reflect environment. The sources of difficulty in separating the contributions of the two factors are largely the same. Development and learning, like genetics and environment, are so complexly intertwined that usually no clear separation of their influence is possible. Further, as the term readiness suggests,
many of the most striking "developmental" phenomena involve differences in learning at different ages (as in the difference in learning of syntax at different ages, documented by Johnson & Newport, 1989). Regardless of whether microgenetic methods are viewed as providing information about learning or development, they allow us to compare the range of experiences that trigger a given change at different ages.

The third defining characteristic of microgenetic methods—in addition to observations that span the entire period of rapid change and a high density of observations within that period—is intensive analysis of both qualitative and quantitative aspects of change. Training experiments and skill-acquisition studies both have involved observation of changes within and across sessions. However, they typically have been limited to descriptions of quantitative changes in speed and/or accuracy. Failure to analyze qualitative as well as quantitative shifts has limited the contribution of such studies to an understanding of change. Consider the impact of failing to assess the types of qualitative changes involved in changes in strategy use. Some improvements in speed and accuracy are due to construction of new strategies; some are due to shifts in the relative frequency of existing strategies; some are due to more efficient execution of the existing strategies. Intensive analysis of strategy use can differentiate what each of these sources of change contributes and when it makes the contribution. This potential for yielding more differentiated descriptions of particular changes is what makes microgenetic methods so promising a source of data about how change occurs.

**History**

The concept of microgenetic methods and the rationale for using them go back at least as far as two of the forefathers of developmental psychology, Heinz Werner and Lev Vygotsky. As early as the mid 1920s, Werner was performing what he termed *genetic experiments*, that is, experiments aimed at depicting the unfolding of successive representations that made up psychological events (e.g., Werner, 1925). For example, he described how repeated presentation of highly similar tones led to increased perceptual differentiation of the tonal space. Although his own microgenetic studies focused on change within a single stimulus presentation or a single experimental session, he also noted that the approach could be applied to processes that continued over hours, days, or weeks (Werner, 1948).

Vygotsky (1978) cited approvingly Werner’s arguments favoring genetic experiments, and argued more generally for studying concepts and skills “in the process of change” (p. 65). He condemned the more usual practice of examining procedures whose development was essentially complete, commenting “Previous investigators have studied reactions in psychological experiments only after they have become fossilized” (p. 68). As an alternative to such desiccated research strategies, Vygotsky advocated studying changes as they occur within and across experimental sessions.

In the ensuing years, a variety of investigators who agree on little else have advocated increased use of this approach. Consider the following testimonials from Piagetian, Vygotskyian, and information-processing-oriented researchers:

The most appropriate method for tracing the evolution of a process such as this is a method which permits the subject to have the opportunity for repeated learning experiences in order to activate his existing schemes and to increase the opportunity for interaction between these schemes and the emergent schemes which result from interaction with the problem environment. The unfolding of the subject’s behavior during these repeated sessions constitutes what might be termed a microgenesis, or in other words, a telescoping of the much longer time span of macrogenetic development. (Inhelder et al., 1976, p. 58; translated from French)

When it is possible to utilize microgenetic analysis, it has the great advantage of allowing the investigator to observe the genetic roots and the final form of a strategy within a single session. When one observes a subject during all phases of strategy development, one can better identify the transitional processes and limit alternate explanations. (Wertsch & Stone, 1978, p. 9)

When questions about transition processes are central, the microgenetic approach seems to be the method of choice. (Siegler & Jenkins, 1989, p. 103)

It is not difficult to see why the method would appeal to those interested in understanding the process of change, regardless of their theoretical orientation. The microgenetic approach can reveal the steps and circumstances that precede a change, the change itself, and the generalization of the change beyond its initial context.

Consider an example of the type of information the method can yield regarding the steps preceding a change. Karmiloff-Smith (1984) noted a consistent pattern in microgenetic experiments she had conducted. Representatives growth frequently followed success rather than failure. That is, children often stopped using approaches that had been producing success on the task and began using alternative approaches instead. Only direct observation of ongoing change could have yielded this type of information.

Next, consider an example of how the approach can yield information about the change itself. Lawler (1985) intensely observed his daughter’s understanding of arithmetic, tie-tac-toe, LOGO, and other skills in the half year following her sixth birthday. He noted a number of insights and discoveries in the course of her learning and found that they tended to occur when two or more competing conceptualizations were suddenly realized to be sufficient to solve the same problem. As he put it, “The elevation of control was not necessity driven, but rather derived from the surprising confluence of results where no such agreement between disparate structures was expected” (p. 63). This view, quite different from the usual stereotype of discovery, illustrates the type of nonintuitive ideas that can emerge from intensive observation of changes.

Now, consider an example of the way in which the microgenetic approach can inform our understanding of
how changes are generalized beyond their initial contexts. Kuhn and Phelps (1982) examined 10- and 11-year-olds' experimentation strategies over an 11-week period (one session/week). They found that even after children discovered a systematic experimentation strategy, they continued to use a variety of unsystematic strategies as well. This was true of literally every subject in their study. Schaubele (1990) reported similar results with the same age group over 8 weekly sessions on a different scientific reasoning problem, and found that the variability was present within as well as between subjects, and at times even within the same subject on a single trial. This variability was paralleled by variability of beliefs about the causal status of variables in the problems. Often, children performed a valid experiment to test the effect of a variable, recognized that the results indicated that the variable had no effect, yet later in the session indicated that the variable did matter. Schaubele described such beliefs as "appearing finally to fade rather than conclusively being rejected" (p. 52). Again, it is difficult to see how such information about change could have been obtained without intensive observation of the process.

The microgenetic approach can further understanding of these three phases of the change process in social as well as solitary contexts. It has proved particularly helpful for investigating the interactions through which teachers and learners, or learners working together, acquire new competencies. In one such study, Sax, Guberman, and Gearhart (1987) examined how mothers teach their preschoolers to play number games. They found that both lower and middle-class mothers adjusted task presentations to their children's level of success on the task. If the child succeeded, the mother proceeded to a higher level goal, which involved less support for the child's problem solving. If the child failed, the mother proceeded to a lower level goal, which involved more direct guidance of the child's efforts. Again, only direct observation of changes during the course of the interaction could produce such finely nuanced descriptions. (See Forman, 1989; Wertsch & Hickman, 1987; and Wood & Middleton, 1975, for related accounts of how social interaction contributes to cognitive growth. Also see Catan, 1986, for a more extensive history of microgenetic methods.)

Current Status

With all of these testimonials and positive examples, one might expect microgenetic experiments to be extremely prevalent. In fact, they are not. There seem to be between 10 and 20 such studies on cognitive development, depending on the stringency of the definition of the term microgenetic study.

The reason for the relative paucity of such experiments is not hard to grasp: They are difficult and time consuming to conduct. Subjects generally must be tested individually to obtain the type of detailed data that is essential for trial-by-trial analyses of performance. Determining when changes occur for each subject requires poring over the videotaped record of performance, transcribing large numbers of verbal statements, and classifying each trial with regard to the approach the subject used. When the validity of strategy classification is an issue, as it often is, converging measures from accuracy and solution time data are also needed to validate the strategy assessments. In addition, the amount of time required for children to make a given change often is difficult to anticipate, highly variable across individuals, and heavily dependent on the fit between the capabilities of the children tested and the demands of the task.

Even if these data collection, coding, and experimental design problems are overcome, complex statistical and presentational issues remain. Analyses of repeated measures data, especially repeated measures categorical data, introduce many difficulties and often demand choosing the lesser evil rather than formulating an ideal solution (Appelbaum & McCall, 1983; Landis & Koch, 1979). The demand of many statistical tests for large numbers of subjects conflicts directly with the practical demand of using samples small enough to allow trial-by-trial analyses of the data. Integrating verbal protocol data, which can convey the flavor of changes, with quantitative data, which provide a more aggregated depiction of the changes, poses challenges of its own. Given all of these difficulties, it is in some ways surprising that any such studies exist.

More than simply existing, however, the prevalence of such studies appears to be growing. One reason is that the availability of high-quality, relatively inexpensive videocassette recorders has made them easier to conduct. Another is that expanding knowledge of the typical course of development has made possible better informed estimates of the most appropriate age groups. However, the most important reason, we believe, is that it is increasingly evident that the value of the data yielded by such studies more than compensates for the logistic and methodological complexities that they entail.

On the logic that the best recommendations for a method are the types of data that it yields and the issues that it allows us to address, we next describe in some detail the issues and findings in one microgenetic study—Siegler and Jenkins's (1989) study of four- and five-year-olds' discovery of the min strategy for adding numbers.

A Microgenetic Study of Strategy Discovery

Background

The min strategy is an approach to adding that involves counting up from the larger addend the number of times indicated by the smaller addend. For example, a child using the min strategy to solve 2 + 5 would start at 5 and count upward 2 counts (the child would think "5, 6, 7"). Some kindergartners and most first, second, and third graders know and use this strategy (Ashcraft, 1982, 1987; Carpenter & Moser, 1982; Geary & Brown, 1991).

Groen and Parkman (1972) hypothesized that young children consistently use the min strategy to solve single-digit addition problems. Their main evidence was that the size of the smaller addend was an excellent predictor
of first graders' mean solution times on different problems. That is, they found that problems such as $6 + 3$, $3 + 6$, and $4 + 3$ all had similar mean solution times and that problems such as $7 + 2$ elicited shorter times and problems such as $5 + 4$, longer ones.

To account for this finding, they proposed the min model. Within this model, children were seen to solve a problem by counting up from the smaller addend. The time to set the counter was assumed to be constant across problems. Thus, variation among problems in solution times was predicted to be a linear function of the number of counts upward, that is, of the size of the smaller (minimum) addend.

Subsequent findings, based primarily on chronometric data, seemed to support this analysis. Consistent with the main prediction of the model, size of the smaller addend was found by a number of investigators to be the best predictor of first and second graders' solution times. It was also found to be a very good predictor in absolute terms, accounting for between 60% and 75% of variance in solution times in a number of experiments (Ashcraft, 1982, 1987; Kaye, Post, Hall, & Dineen, 1986; Svensson, 1975). These studies included children with learning disabilities as well as children without such problems, and children in Europe as well as children in North America (Svensson & Broquist, 1975). The model was also found to fit individual children's solution times as well as group averages (Groen & Resnick, 1977; Kaye et al., 1986; Svensson, 1975).

The one discordant note came from mathematics educators' descriptions of what children said they did to solve addition problems (e.g., Carpenter & Moser, 1982; Fuson, 1982). The children reported using a variety of strategies, with some describing five or more distinct approaches.

The divergence between these reports and the min model suggested two alternatives. One was that the children's verbal reports were inaccurate. Even adults' verbal reports are often misleading (Nisbett & Wilson, 1977); young children might have yet greater difficulty (Brainerd, 1973). The other possibility was that the verbal reports were accurate, and that the results of the chronometric analyses did not in fact imply consistent use of the min strategy.

To distinguish between these alternatives, Siegler (1987) presented kindergartners, first graders, and second graders simple addition problems and collected both solution times and verbal reports of strategy use immediately following each problem. The results replicated the findings of both the chronometric and the verbal protocol studies. Consistent with the chronometric studies, the min model was the best predictor of median solution times on each problem, accounting for 76% of the variance in the times. Consistent with the protocol studies, children reported using not only the min strategy but also the sum strategy (representing the first addend, representing the second addend, and then counting from one to the sum of the addends), decomposition (e.g., $9 + 4 = 10 + 4 - 1$), retrieving answers from memory, and guessing. The diversity of strategy use characterized individual children as well as the group; most children reported using at least three strategies. Overall, children reported using the min strategy on only 36% of trials.

Thus, the question remained: Were children consistently using the min strategy to add, or were they using multiple strategies? To find out, solution times on each problem were divided according to the strategy that children were classified as using on the basis of their verbal report and the videotape of their nonverbal behavior during the problem.

Separating solution times according to the strategy classifications yielded a clear pattern. On trials in which children were classified as using the min strategy, the min model was an even better predictor of solution times on each problem than in past studies or in this data set as a whole. Size of the smaller addend accounted for 86% of the variance in solution times. In contrast, on trials in which they used a different strategy, the min model was not a good predictor of solution times in either absolute or relative terms. It never accounted for as much as 40% of the variance and never was either the best or the second best predictor of solution times for any of the other strategies. These and a variety of other data converged in indicating that children used multiple strategies and that they used them on the problems where they said they did. (See Siegler, 1987, for a statistical analysis of why the min model was such a good predictor of the overall solution times when the strategy was used only on a minority of trials.)

These findings provided essential background information for the microgenetic experiment on acquisition of the min strategy. They indicated that some five-year-olds and almost all six-year-olds knew the min strategy. This suggested that four- and five-year-olds would be a good population for examining its acquisition. The findings also provided convergent validation for the combination of videotaped records of ongoing problem solving and immediately retrospective verbal reports as a method for assessing strategy use on each trial. Finally, the findings provided a context for understanding the data yielded by the new experiment. For example, knowing that second graders, who presumably had been using the min strategy for at least a year, continued to use a variety of other strategies as well as the min approach, provided a different perspective on variability in strategy use following the initial discovery than if the second graders had used the min strategy on 100% of trials. More generally, microgenetic experiments seem most likely to succeed in areas in which previous studies indicate appropriate age groups, assessment techniques, and descriptions of typical development that provide context for interpreting findings.

The Microgenetic Experiment

The Siegler and Jenkins (1989) experiment included two main parts: a pretest and an 11-week practice period. In both parts, children were tested individually and their strategy use was assessed on each trial. Strategy assessment
involved a combination of videotaping and asking the child immediately after each trial how he or she had solved the problem. When overt behavior indicated how the child had solved the problem, it provided the basis of strategy classification on that trial. When overt behavior was ambiguous or absent, the immediately retrospective reports provided the basis of classification. Converging evidence for the validity of strategy assessments obtained in this way has been provided by solution time and accuracy data (Siegel, 1987, 1989a). Obtaining the self-reports also has been found not to influence the strategy use itself, as indicated by highly similar frequencies and patterns of overt strategic behavior when verbal reports are and are not requested (McGilly & Siegel, 1990).

The pretest was used to select four- and five-year-olds who did not already know the min strategy but who possessed some skill in adding numbers. Children were presented simple addition problems with addends 1–5. They were asked after each trial how they had solved the problem. In another part of the pretest, they were asked repeatedly to recommend possible ways of adding numbers to a hypothetical younger child until they said they did not know any more ways to recommend. Data were also collected on the children’s counting and magnitude comparison skills. (See Siegel & Jenkins, 1989, for a more detailed presentation of this and other aspects of the study.)

The children who were selected to participate in the practice phase were those who did not report counting from a number greater than one on any of the pretest problems, did not give evidence of doing so on the videotapes of their ongoing problem-solving activities, and did not recommend any such strategy to the hypothetical younger child. To guarantee reasonable prior knowledge of addition, children also needed to answer correctly at least 50% of the problems.

This selection procedure resulted in 10 children being selected for participation in the practice period. These children correctly answered 78% of the addition problems on the pretest. The sum strategy (counting from 1) was their most frequent approach; they used it on 43% of the pretest addition problems.

The 11-week practice period involved approximately three sessions per week for each child. In general, seven problems were presented in each session. The only exception was the session (if any) in which the child first used the min strategy. In that session, the experimenter presented several further problems to probe the nature of the child’s understanding at the time of the discovery. Previous evidence (Groen & Resnick, 1977; Resnick & Ford, 1981) indicated that children ordinarily invent the min strategy simply on the basis of solving addition problems, rather than being taught it by teachers or textbooks. This led to the expectation that the experimental conditions would be effective in eliciting the discovery and that they would approximate the conditions under which children typically construct the min strategy.

All but two of the children in this sample completed the 11-week practice period. One child did not finish because she took the situation so seriously that she became upset when she answered incorrectly. The other child failed to finish for the opposite reason; he gave extensive evidence of not trying. Furthermore, a minor epidemic of flu and colds resulted in children completing varying numbers of sessions (18–34) and trials (130–244). Both attrition and absenteeism are problems that are likely to arise in many long-term microgenetic studies. Including more subjects and more sessions than the minimum expected to be necessary seems essential for success in such circumstances.

The original plan was to present repeatedly the problems with addends 1–5 until all of the children discovered the min strategy. The logic followed that of Case’s (1985) theory: Discovery of new strategies would occur most often when processing was highly automatized and substantial processing resources were available. This approach was effective to an extent. After seven weeks of the practice period, five of the eight children had made the discovery, in the sense of using the new strategy at least once. However, they tended to use it only occasionally.

This led to adoption of a necessity-is-the-mother-of-invention perspective. To create a need to use the min strategy, the experimenter presented challenge problems during Week 8. These were problems such as 2 + 21, that is, problems with one large and one small addend. These challenge problems provided both a carrot and a stick for using the min strategy—the carrot because such problems could be solved quite easily by counting from the larger addend, the stick because the children’s other strategies, such as the sum strategy and retrieval, could not be easily executed on them. Finally, in the period following the challenge problems (Weeks 9–11), children were presented a mix of problems, ranging from 2 + 1 to 22 + 4, with all gradations of difficulty in between.

**Overview of Findings**

Microgenetic experiments can yield the same types of data on speed and accuracy as more conventional designs, as well as other data that are unique to them. The more typical data are especially useful for establishing overall levels of performance.

Summed over the 11-week practice phase, the accuracy of individual children ranged from 76% to 98% correct; the mean was 85%. All children usually advanced the correct answer on small addend problems (problems with both addends no greater than 5), with individual children’s percentage correct ranging from 81% to 100%. Performance on large addend problems (those with at least one addend above 5) was more variable, with individual children’s accuracy ranging from 42% to 94%. Percentage correct on the small addend problems, the only ones that were presented throughout the experiment, changed substantially over the course of trial blocks (blocks of five sessions each), improving from 80% correct in children’s first trial block to 96% correct in their final one.
Table 1
Percentage Use, Percentage Correct, and Median Reaction Time (RT) for Each Strategy

<table>
<thead>
<tr>
<th>Strategy</th>
<th>Percentage use</th>
<th>Percentage correct</th>
<th>Min RT</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sum</td>
<td>34</td>
<td>89</td>
<td>10.8</td>
</tr>
<tr>
<td>Retrieval</td>
<td>22</td>
<td>89</td>
<td>5.0</td>
</tr>
<tr>
<td>Short-cut sum</td>
<td>17</td>
<td>85</td>
<td>13.2</td>
</tr>
<tr>
<td>Finger recognition</td>
<td>11</td>
<td>92</td>
<td>6.4</td>
</tr>
<tr>
<td>Min</td>
<td>9</td>
<td>86</td>
<td>9.0</td>
</tr>
<tr>
<td>Guess</td>
<td>2</td>
<td>20</td>
<td>9.9</td>
</tr>
<tr>
<td>Count-from-first</td>
<td>1</td>
<td>40</td>
<td>15.6</td>
</tr>
<tr>
<td>Unknown</td>
<td>4</td>
<td>71</td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>100</td>
<td>85</td>
<td>9.4</td>
</tr>
</tbody>
</table>


Children used a number of strategies to solve problems. The most frequent ones are illustrated in Table 1. Across all children, the sum strategy and retrieval were the approaches used most often, with the two strategies being employed on 34% and 22% of trials, respectively. As might be expected, there was some movement over trial blocks toward greater use of the more advanced strategies (retrieval and the min strategy) and less use of the less advanced approaches (guessing and the sum strategy).

More striking, however, was the variability in children’s strategy use. Variability was apparent at two levels. One was in the number of strategies used by each child. As shown in Table 2, each child used at least five strategies. The second type of variability was the relative frequency of use of each strategy by different children. Use of the sum strategy ranged from 0% to 69%, use of retrieval from 1% to 61%, use of finger recognition from 0% to 25%, and so on. This variability could not be explained entirely as the result of more knowledgeable children using the more advanced approaches, such as retrieval. There was some relation between knowledge and use of the more advanced strategies, but it was far from perfect. The child who used retrieval on the greatest percentage of trials ranked seventh among the eight children in percentage correct. The child who produced the highest percentage correct was only fourth highest in percentage use of retrieval. This was not an isolated finding. There were exceptions to even the most regular relations in the study; the extensive data collected on each subject made it difficult to dismiss these exceptions as random occurrences or reflections of measurement error. Such results from this and other microgenetic studies indicate that theoretical accounts need to explain the variability as well as the consistencies that characterize performance and change.

The central focus of the study was not on speed, accuracy, or overall strategy use, however, but rather on discovery of the new strategy. It is here that the advantages of microgenetic methods are greatest. Next we describe the discovery itself, precursors that led up to it, and generalization beyond its initial use.

Discovering a New Strategy

The largest risk in conducting a microgenetic study is that the change of interest may not occur in the available time. Fortunately, this problem did not arise here. Over the 11 weeks, seven of the eight children made the discovery. The time that they required varied greatly. The first discovery occurred in the 2nd session of the experiment, on the particular child’s 6th trial. The last discovery occurred in the 30th session, on the 209th of the 210 trials that that child encountered. Other discoveries were spaced rather evenly in between.

Quality of the discoveries. Microgenetic studies allow observation of discoveries as they are being made,

Table 2
Percentage Use of Each Strategy by Each Child

<table>
<thead>
<tr>
<th>Child</th>
<th>Sum</th>
<th>Retrieval</th>
<th>Short-cut sum</th>
<th>Finger recognition</th>
<th>Min</th>
<th>Guess</th>
<th>Count from first</th>
<th>Unknown</th>
</tr>
</thead>
<tbody>
<tr>
<td>Brittany</td>
<td>43</td>
<td>6</td>
<td>9</td>
<td>19</td>
<td>21</td>
<td>1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Christian</td>
<td>31</td>
<td>10</td>
<td>27</td>
<td>25</td>
<td>1</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Danny</td>
<td>65</td>
<td>1</td>
<td>6</td>
<td>13</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Jesse</td>
<td>0</td>
<td>23</td>
<td>68</td>
<td>1</td>
<td>2</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Laine</td>
<td>69</td>
<td>5</td>
<td>1</td>
<td>6</td>
<td>1</td>
<td>17</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Lauren</td>
<td>40</td>
<td>40</td>
<td>8</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ruth</td>
<td>13</td>
<td>42</td>
<td>9</td>
<td></td>
<td>8</td>
<td>17</td>
<td>2</td>
<td>1</td>
</tr>
<tr>
<td>Whitney</td>
<td>5</td>
<td>61</td>
<td>5</td>
<td></td>
<td>5</td>
<td>18</td>
<td>2</td>
<td>3</td>
</tr>
<tr>
<td>Total</td>
<td>34</td>
<td>22</td>
<td>17</td>
<td>11</td>
<td>9</td>
<td>2</td>
<td>1</td>
<td>4</td>
</tr>
</tbody>
</table>

Note. The notation "—" indicates the strategy was never used. The notation "0" indicates that it was used, but on less than .5% of trials. Data are from How Children Discover New Strategies (p. 61), by R. S. Siegler and E. Jenkins, 1989. Hillsdale, NJ: Erlbaum. Copyright 1989 by Lawrence Erlbaum Associates. Reprinted by permission.
and thus can convey a qualitative sense of the discovery process. The following protocol was taken from the trial on which one five-year-old girl first used the min strategy. (The names of children cited here and throughout the article are aliases.)

E: OK Brittany, how much is 2 + 5?
B: 2 + 5 — [whispers] 6, 7 — it’s 7.
E: How did you know that?
B: [excitedly] Never counted.
E: You didn’t count?
B: Just said it — I just said after 6 something — 7 — 6, 7.
E: You did? Why did you say 6, 7?
B: Cause I wanted to see what it really was.
E: OK, well — so, did you — what — you didn’t have to start at one, you didn’t count 1, 2, 3, you just said 6, 7?
B: Yeah — smart answer.

This protocol fits well with the common prototype of discovery, which is probably Archimedes shouting “eureka” following his insight in the bathtub concerning how to test whether the king’s crown was pure gold. This prototype entails awareness of what has been done, realization that it is important, and excitement at making the discovery.

Other children’s discoveries showed none of these properties, however. Consider Whitney’s protocol:

E: How much is 4 + 3?
W: 5, 6, 7, I think it’s 7.
E: 7, OK, how did you know that?
W: Because I’m smart and I just knew it.
E: Can you tell me, I heard you counting. I heard you. Tell me how you counted.
W: I just — I didn’t count anything — [long pause] I just added numbers onto it.
E: Can you tell me how you added numbers?
W: No.
E: Come on Whitney — come on, we have to do this, OK?
W: OK [in a bored voice], 3, add one makes 4, add one makes 5, add one makes 6, add one makes 7, add one makes 8.
E: Wait, but how did you know what 4 + 3 was?
W: Cause I did what I just showed you. I just used my mouth to figure it out.

Unlike Brittany, Whitney showed little awareness of what she had done (she first said that she just knew it, and the counting that she reported in the protocol was not the counting that was recorded on the videotape). She also displayed little affect during or immediately after her first use of the new strategy.

Whitney’s and Brittany’s protocols were not atypical; indeed, we quoted them because they were representative. The most insightful first uses of the strategy showed surprising understanding of why the new strategy was desirable. For example, Ruth explained why she had counted from 4 on 4 + 3 by saying that “I don’t have to count a very long ways if I start from 4, I just have to do 3 more.” At the other extreme, some children insisted that they had retrieved the answer from memory, despite the videotapes containing audible counting from the larger addend. Thus, strategy discoveries clearly entail a wide range of degrees of awareness, insight into implications, and affective reactions.

The role of impasses in discoveries. What types of problems give rise to discoveries? One common view is that discoveries generally occur on difficult problems that cannot be solved in other ways. This view is often labeled impasse driven learning.

Discoveries of the min strategy were inconsistent with this view, however. The problems on which discoveries were made were quite representative of the total set of problems that children encountered: 2 + 5, 5 + 2, 4 + 1, 3 + 9, 1 + 24, and 4 + 3 (twice). Apparently, discoveries can occur in the course of solving easy problems, difficult problems, or problems of middling difficulty. Further, most of the discoveries came on problems that, earlier in the experiment, the particular child had solved correctly without any apparent difficulty.

These findings were directly at odds both with traditional views of learning and with a number of current artificial intelligence and theoretical linguistics models of strategy construction (e.g., Newell’s, 1990, SOAR model; VanLehn’s, 1988, RT2 model; and Wexler & Culicover’s, 1980, and Berwick’s, 1987, syntax acquisition models). VanLehn succinctly stated the basic assumption of these models regarding how new procedures are learned: “Learning occurs only when an impasse occurs. If there is no impasse, there is no learning” (pp. 31–32).

There is no question that changes often do take place in response to impasses and failure. However, it is becoming increasingly evident that in many situations, changes occur under other circumstances as well. For example, children initially solve class inclusion problems by counting the number of objects in the total set, counting the number of objects in the larger subordinate set, and then comparing the results of the two counts. Although this approach typically yields perfect performance, older children do not use it. Instead, they base their conclusions on the logic that the superordinate set must necessarily have more objects (Markman, 1978). Similarly, in number conservation, young children solve problems by counting and comparing the number of objects in the two rows. Again, despite this approach yielding consistently correct performance, older children shift away from it. They base answers on the reasoning that just spreading out or contracting a row could not change the number of objects (Siegler, 1981). In map drawing, children shift without any negative feedback or impasse from simple correct notations to ones with more redundancy (Karmiloff-Smith, 1984). In language use, they shift from consistent correct use of verbs such as dropped and fell to incorrect use, again without any apparent external pressure. After noting several such cases, Bowerman (1987) concluded “Our theory of language acquisition is going to have to explain what causes grammars to change
even when children receive no overt evidence that there is anything wrong with their current grammars” (p. 459).

These observations point to a basic inadequacy in prevailing approaches to cognitive development. Flavell (1971) noted that one shortcoming of stage theories was that within them, “the individual spends virtually all of his childhood years ‘being’ rather than becoming” (pp. 426–427). The criticism applies not just to stage theories but to all approaches that depict change in terms of static states punctuated by occasional episodes of change. Assuming that thinking changes only under duress—or only when some maturational constraint has been satisfied—relegates change to a conditional status. Yet, the examples of conceptual development, language development, and development of problem-solving skills that were cited in the previous paragraphs suggest that it may be more accurate to view change, rather than static states, as the norm. Other types of evidence point in the same direction.

The ubiquity of the practice law (Newell & Rosenbloom, 1981) has been found to reflect a continuous stream of qualitative and quantitative changes that occur across extremely diverse content domains (Agre & Shragar, 1990; Cheng, 1985; Hirst, Spelke, Reaves, Cahanack, & Neisser, 1980). The success of self-modifying artificial intelligence models, such as Holland, Holyoak, Nisbett, and Thagard’s (1986) genetic algorithm, rests in large part on change being integral to the overall program. Similarly, the success of Klahr and Wallace’s (1976) production system models depended critically on their detecting regularities in the time line even when there was no external pressure to do so. The large amount of subject-to-subject variability observed in this and other microgenetic studies in every part of the strategy construction process is a natural, though not a necessary, concomitant of this perspective.

One desirable consequence of viewing variation and change as integral parts of ongoing cognitive activity is that it makes explaining cognitive growth far less problematic. Mechanisms that produce a steady stream of variations would provide the raw material from which innovations could emerge. Mechanisms of selection would then differentially maintain those innovations that produced useful outcomes. Consistent with this analysis, the best-worked-out recent models of cognitive development have included variation-producing mechanisms. Three examples are MacWhinney, Leinbach, Taraban, and MacDonal’s (1989) model of language acquisition, Holland et al.’s (1986) model of the development of encoding, and Gentner’s (1989) model of the development of analogical reasoning. Each of these illustrates how variation-producing mechanisms might operate. Recent findings in developmental neurophysiology also have demonstrated that initial overproduction and subsequent pruning of synapses is involved in many age- and experientially related changes in cognitive functioning (e.g., Goldman-Rakic, 1987; Greenough, Black, & Wallace, 1987; Huttenlocher, 1979). Viewing change as continual, rather than sporadic or periodic, promises to lead to more viable accounts of cognitive development.

Discoveries that were not made. Just as the micro-

genetic design yielded data about the nature of discoveries that were made, it also yielded evidence about discoveries that were not made. The situation was reminiscent of the classic conversation in The Memoirs of Sherlock Holmes:

Holmes: But there was the curious incident of the dog in the nighttime.
Watson: The dog did nothing in the nighttime.
Holmes: That was the curious incident.

In Siegler and Jenkins (1989), the curious incident was that not one child ever used a strategy that violated the principles underlying addition. Several potential illegitimate strategies were superficially similar to legitimate approaches and therefore could easily have been tried. For example, children might have tried counting the first addend twice, or counting on from the second addend the number of times indicated by the larger addend, regardless of whether it was first or second. In fact, not one child used these or other illegitimate strategies on even one trial. This raised the question, Why not?

Goal sketches. Siegler and Jenkins (1989) suggested one potential answer to this question: The strategy generation process was constrained by a goal sketch, which specified the hierarchy of objectives that a satisfactory strategy needed to meet. In general, such a hierarchical structure would direct searches of existing knowledge toward procedures that could meet the goals. In so doing, it also would direct searches away from illegitimate procedures. The goal sketch for addition might be realized as a pair of productions:

P1: IF your goal is to add two numbers and you know the number that quantitatively represents their sum
THEN state that number.
P2: IF your goal is to add two numbers and you do not know the number that quantitatively represents the two sets
THEN set as subgoals
1. To symbolically represent each addend in the original problem.
2. To quantitatively represent the objects in the combined symbolic representation.

This goal sketch would exclude illegitimate strategies. For example, both of the aforementioned illegitimate strategies would be ruled out because they did not include a representation of each addend, as specified in the first subgoal of P2.

The goal sketch also has another empirical implication: Children who possess such knowledge should recognize the superiority of strategies that meet the goals over strategies that do not. Such discrimination should be evident even among children who do not know either the legitimate or the illegitimate strategies, if they possess the goal sketch and perceive the relation of the novel strategies to it. Consistent with this implication, Reeve and Humphal (1989) reported that five-year-olds who did
not yet use the min strategy nonetheless judged it superior to other strategies that violated the goals of addition.

The goal sketch described earlier by P1 and P2 reflects only the inherent logic of the task, addition. It also seems likely, however, that goal sketches can be expanded to include circumstantial constraints when the situation calls for them. For example, in Gelman and Gallistel's (1978) order invariance experiment, children were asked to obey the usual rules of counting and also to conform to the experimenter's request to assign a specific number to a specific object. The request might be to count a row of five objects in such a way that the left-most object was labeled 4. By age five, most children succeeded in meeting both the standard rules of counting and these further stipulations. This finding, together with five-year-olds' consistent discrimination between those counting procedures that violate counting principles and those procedures that are odd but legitimate (Briars & Siegler, 1984; Gelman, Meck, & Merkin, 1986), suggests that five-year-olds' goal sketches for counting are permeable to the demands of the particular situation and reflect the basic hierarchy of goals in the domain. This seems likely to be a property of goal sketches in many domains.

Although they clearly are not the only mechanism involved, goal sketches also may contribute to construction of new, legitimate strategies. Findings from Siegler and Jenkins (1989) illustrate this point. Even before children discovered the min strategy, they gave evidence of possessing most components of it. These included identifying the larger of two numbers, reversing the addend order, counting on from numbers greater than one, and simultaneously keeping track of two sets of counts (essential for stopping at the right point in the min strategy). The one component that appeared to be missing was the realization that a number can be represented quantitatively by simply restating the number and using it to represent the quantity associated with it. Although this seems a simple realization, Secada, Fuson, and Hall (1983) found that many children lacked it and that the lack was associated with absence of the min strategy.

If children did not possess this knowledge, how might they acquire it? The goal-sketch construct suggests that one fruitful place to look is to components of existing strategies. The reason is that these components of existing strategies are directed at meeting the same goals that components of the new strategy must meet—that is, the goals and subgoals within the goal sketch.

Consistent with this analysis, changes during the Siegler and Jenkins (1989) study in children's execution of existing strategies appeared critical for construction of the missing component. As children gained practice using the sum strategy, they increasingly represented the value of each addend by putting up that number of fingers without counting them out. For example, if asked to solve 4 + 2, they simply raised four fingers, rather than counting 1, 2, 3, 4. In the course of the study, children also became increasingly adept at recognizing the number of fingers they had put up. That is, on a problem like 3 + 1, once they had put up three fingers on one hand and one on the other, they increasingly often said "4" without any apparent counting. This suggests that through the process of composition (Anderson, 1983), children who already possessed P3 and P4 might generate the missing production, P5.

P3: IF your goal is to quantitatively represent \( N \),
THEN put up \( N \) fingers.

P4: IF your goal is to quantitatively represent \( N \) and
you have put up \( N \) fingers,
THEN say "\( N \)" to represent the quantity.

P5: IF your goal is to quantitatively represent \( N \),
THEN say "\( N \)" to represent the quantity.

Creation of the knowledge represented in P5 seems to have removed the last obstacle to children using the min strategy. Once P5 was created, it would meet the subgoal within the goal sketch of providing a means of representing a number quantitatively, and thus could be used in the construction of the min strategy. (See Siegler & Jenkins, 1989, for a more extensive discussion of the strategy construction process.)

Regardless of the correctness of the particular account, this analysis has several general implications. First, individual mechanisms such as the goal sketch may influence both which strategies are discovered and which are not. Second, construction of appropriate new strategies seems to require both conceptual knowledge akin to that represented in the goal sketch and knowledge of procedures that serve as components of strategies for meeting the goals. Third, components of existing strategies may often be a useful source of components for new strategies because they are directed at meeting the same goals. Fourth, microgenetic methods can yield data that are valuable for constraining hypotheses about mechanisms. Only by densely sampling strategy use prior to and during construction of the new approach could we have learned anything about which components presented the final obstacles to the discovery, about improvements in existing strategies that may have made possible construction of an essential component within the new strategy, or about children never using illegitimate strategies.

**Precursors of the Discovery**

The role of impasses. As noted earlier, children did not usually discover the min strategy on problems that were unusual or difficult relative to other problems they encountered in the experiment. Most discoveries came on problems that they previously had solved correctly through application of other addition strategies. The possibility remained, however, that children's discoveries were still being driven by impasses—not on the discovery problem but on problems encountered immediately preceding the discovery. If this were the case, the prior impasses may have stimulated cognitive activity that, over the course of several problems, coalesced into the new strategy.
The relevant data, performance on problems earlier in the same session in which the discovery was made, did not support this interpretation. The preceding problems were not unusually difficult; 88% were small addend problems, versus 72% for all sessions combined. Children did not usually fail on them; they answered 75% correctly, versus 85% for the experiment as a whole. Furthermore, one child contributed three of the four errors; the others were correct on more than 90% of the preceding trials. All of the children were correct on the trial immediately before the discovery.

The unusual feature of children's performance just before the discovery was the very long solution times. Children took twice as long to solve problems in the same session but before the discovery as on problems in general (medians of 18 vs. 9 seconds). In addition to long solution times, these preceding trials were often marked by verbalizations that indicated partial execution of a strategy, followed by long pauses and/or strange statements that resisted straightforward interpretation. The unusual protocols, combined with the increased solution times, suggest that immediately before the discovery, children began to experience increased cognitive activity, which culminated in creation of the new strategy. However, because the problems children encountered just before the discovery were representative in difficulty of the overall set of problems, and because children performed quite accurately on them, the problems did not present impasses in any usual sense of the term.

**Transition strategies.** A number of investigators have suggested that the count-from-first strategy mediates the transition between the sum and min approaches (Groen & Resnick, 1977; Neches, 1987; Resnick & Neches, 1984; Secada et al., 1983). A child who used this count-from-first strategy would solve 2 + 4 by counting "2, 3, 4, 5, 6" and would solve 4 + 2 by counting "4, 5, 6." This seemed a very plausible candidate for a transition strategy because it included one, but not the other, of the two main innovations of the min strategy. Like the min strategy, it involved beginning to count at a point corresponding to one of the addends rather than always beginning at the number 1. Unlike the min strategy, however, it involved always counting from the first addend, regardless of whether it was larger or smaller than the second. Once children realized that they always obtained the same answer on a + b as on b + a, and that less counting was needed when the larger addend was first, they would complete the transition to the min strategy.

Groen and Resnick (1977) searched for evidence for this strategy in their chronological study of early addition. In particular, they examined whether the size of the second addend was ever the best predictor of solution times, as would occur if counting from the first addend was the dominant strategy. This pattern was not evident in any child's performance. Nonetheless, Groen and Resnick correctly noted that a chronometric analysis, such as the one they used, would not detect such a transition strategy if it was used only briefly or sporadically. On this logic, Neches (1987; see also Resnick & Neches, 1984) made the count-from-first strategy the key transition approach within a very elaborate computer simulation of acquisition of the min strategy. Much of the simulation was devoted to accounting for how children made the transition from the sum strategy to counting from the first addend and to how they then made the transition from counting from the first addend to the min strategy.

The trial-by-trial data yielded by Siegler and Jenkins's (1989) microgenetic experiment, however, demonstrated conclusively that counting from the first addend does not in general mediate discovery of the min strategy. Only one of the eight children ever counted from the first addend on trials in which it was not also the larger addend. That child only began using the strategy after she had already used the min strategy. Thus, the hypothesized transition strategy was in fact transitional for none of the eight children.

The microgenetic data suggested that a different strategy, the short-cut sum strategy, may be critical to the transition. Like counting from the first addend, it contains some but not all of the innovations of the min approach. The particulars are different, though. It is like the sum strategy in that it involves starting at one and counting all of the numbers between one and the sum of the addends. It is like the min strategy in that representation of the second addend and its addition to the running total take place simultaneously. Thus, on 4 + 2, a child using the short-cut sum strategy would count "1, 2, 3, 4—5, 6" rather than "1, 2, 3, 4—1, 2—1, 2, 3, 4, 5, 6," as the sum strategy would dictate, or "4, 5, 6," as the min strategy would dictate.

Use of the short-cut sum strategy emerged prior to use of the min strategy in all seven children who discovered the min strategy during the experiment. For five of them, it emerged no more than two sessions before they discovered the min strategy: Two first used it two sessions before they first used the min strategy, one first used it one session before, and two first used it earlier in the same session in which they discovered the min strategy. Interestingly, because the short-cut sum strategy, like the traditional sum approach, produces solution times proportional to the sum of the addends, there is no obvious way that chronometric or accuracy data could ever have led to its identification, regardless of how often it was used. In sum, the data illustrate how microgenetic approaches can both disconfirm hypotheses about transition strategies and suggest alternative ones.

**Generalization of the Discovery.**

Discovery of the min strategy did not quickly lead to its widespread generalization. Even children who eventually generalized the strategy quite widely used it only occasionally at first. For example, the two children who eventually used the strategy on the highest percentages of trials of any participant used it on only 7 of 84 and 2 of 49 trials following their discoveries. Again, this ran counter to the eureka stereotype, in which discovery of a new approach leads to its immediate application. The finding raises the issue of what it means to say
that someone has made a discovery. One possibility is to reserve the term for uses in which the person can adequately explain the logic underlying the new acquisition. Adopting this standard would not appreciably change the pattern described earlier, though. None of the children used the min strategy much before they encountered the challenge problems (the problems such as 2 + 21 that were presented in Week 8), despite several children having clearly explained the advantages of the min strategy on the trial on which they first used it. More generally, defining discovery in this way evades the issue of what such uses without explanations signified.

Another possibility is to define use of a new strategy as a discovery only if initial uses lead to extensive subsequent use. However, this could also lead to large problems. One problem is arbitrariness; how much subsequent use is enough to conclude that a strategy has been discovered? Another problem, again, is evasion of the issue. If the first use is not the discovery, what is it?

A more useful conceptualization may be to recognize that discovery of a strategy is frequently just the first step toward its mastery. Only as people use new concepts and strategies, and experience their consequences, do they fully comprehend their advantages, disadvantages, and conditions of applicability.

Children may be especially susceptible to the limited insight that this perspective implies. However, adults—even the most innovative scientists—are also far from immune. Wegener (1929/1966), the father of plate tectonic theory, described his theory as originating in 1910 or 1911, as a result of his being struck at that point “by the congruence of the coastlines on either side of the Atlantic” (p. 1). Yet Giere (1988) noted that a fellow graduate student recalled that Wegener was struck by this same congruence, and talked about it often, in 1903. Giere commented, “If that is so, the idea lay fallow in Wegener’s brain for a long time before 1911” (p. 230). With great scientists, as with children, understanding of one’s own ideas often may come only with their use.

The role of impasses. As discussed earlier, impasses were not evident either on the trial in which the min strategy was first used or on the trials leading up to the discovery. However, they played a critical role in children’s generalization of the strategy.

Recall that in the eighth week of the practice period, children were presented challenge problems such as 22 + 3. Such problems did not facilitate discovery of the min strategy; none of the three children who had not previously used the min strategy did so in response to this set of challenge problems. However, the problems did have a large impact on generalization of the strategy among the five children who had used the min approach previously. Use of the strategy, which had been below 20% of trials on which the children counted, immediately jumped to 60% of the challenge problems on which counting occurred (Figure 1). The use continued to increase in the last three weeks of the experiment, eventually reaching 90% of trials on which children used counting strategies. The change was also evident when considera-

<table>
<thead>
<tr>
<th>Trial Block (O-Challenge Problems)</th>
<th>Min Strategy Trials</th>
<th>All Counting Trials</th>
</tr>
</thead>
<tbody>
<tr>
<td>-3</td>
<td>10</td>
<td>10</td>
</tr>
<tr>
<td>-2</td>
<td>20</td>
<td>20</td>
</tr>
<tr>
<td>-1</td>
<td>30</td>
<td>30</td>
</tr>
<tr>
<td>0</td>
<td>40</td>
<td>40</td>
</tr>
<tr>
<td>1</td>
<td>50</td>
<td>50</td>
</tr>
<tr>
<td>2</td>
<td>60</td>
<td>60</td>
</tr>
</tbody>
</table>


tion was limited to the small addend problems that were used predominantly early in the study and mixed among other problems later. Here, use of the min strategy increased from less than 20% of counting trials in each of the trial blocks before the challenge problems to 45% after them. The change was striking in four of the five individual children; the fifth rarely used the min strategy either before or after the challenge problems.

These findings suggest that impasses play an important role in learning, but not necessarily the role that usually has been attributed to them. Impasses may be especially effective in promoting the use of strategies that have already been discovered but that have been used only occasionally. In particular, the impasses could lead to more elaborate encoding and memory representations of the strategies themselves, the problems on which they are used, and the sources of difficulty posed by the problems. This elaborated encoding would heighten the accessibility of these previously rare approaches, which in turn would increase subsequent use of them.

This view suggests that the automaticity perspective and the necessity-is-the-mother-of-invention perspective are not incompatible. As suggested by Case (1985), among others, it may generally be easier to construct strategies in the context of well-known content. As suggested by Newell (1990) and Van Lehn (1988), among others, impasses may promote learning. The difference may be in the point within the discovery-generalization sequence at which attention is focused. Initial discovery may occur most often on simple problems; subsequent generalization may occur most dramatically when problems present obstacles that can only be overcome through use of the new strategy. Here, as in many cases, the Siegler and Jenkins (1989) data are not definitive—too few subjects, nonrandom sequencing of easy and difficult problems, design
limited to a single discovery and a single age group—but they do demonstrate the potential of microgenetic studies to provide critical information for refining theoretical analyses of such issues as the role of impasses in discovery and generalization.

Conclusions
The studies described in this article illustrate some of the benefits of studying change as it occurs. Such studies can convey both quantitative and qualitative aspects of change. They can indicate the conditions under which changes are most frequent and allow observation of short-lived transition strategies that would not be detected within chronometric or other more aggregated analyses. They can yield conclusive data about strategies that are not used, as well as about ones that are. They can convey a sense of the process as well as the products of social interaction. These types of data should contribute to improved future theorizing about change mechanisms.

Especially encouraging, microgenetic experiments have yielded closely parallel results across quite diverse changes. One such finding involves the halting and uneven use of newly acquired competencies. Even after children discover sophisticated scientific experimentation strategies, they often continue to use less sophisticated ones as well (Kuhn, Amsel, & O’Loughlin, 1988; Kuhn & Phelps, 1982; Schauble, 1990). When they discover a new problem-solving method with the help of their mothers, they may later fall back on shared control rather than continuing to exert sole responsibility for its execution (Wertsch & Hickmann, 1987). New concepts about the workings of gears are applied in a similarly sporadic fashion (Metz, 1985), as are new strategies for adding numbers (Siegler & Jenkins, 1989).

Another common finding of microgenetic studies is that innovations occur following successes as well as failures. Discoveries have been found to follow successes, rather than impasses or errors, in many children’s map drawing and language use (Karmiloff-Smith, 1984), arithmetic (Siegler & Jenkins, 1989), pictorial representations (Inhelder et al., 1976), and scientific experimentation strategies, (Kuhn et al., 1988; Kuhn & Phelps, 1982; Schauble, 1990). These findings point to the importance of observing in a variety of domains the frequency and types of variation produced without apparent external motivation. They also point to the importance of investigating internal motivations for cognitive change, such as interest (Renninger & Wozniak, 1985) and desire for meta-procedural understanding (Bowerman, 1982; Karmiloff-Smith, 1984). More generally, they point to the need for understanding in detail the mechanisms that produce cognitive variation in the absence of external pressure.

These two commonly observed phenomena may at a deeper level constitute two realizations of the same phenomenon: Cognition and cognitive growth are far more variable than our models typically suggest (Griffin & Cole, 1984; Kessen, 1984; Klahr & Wallace, 1976). People often use multiple strategies where they have been depicted as using only one. The most accurate children tend to use the more advanced strategies, but sometimes do not. Long solution times precede many, but not all, children’s discoveries. Discoveries are made following successes as well as failures, and are often used sporadically once they are made. Unambiguous documentation of this variability may provide the impetus for future models that will account for it and explain its role in producing change. Stimulating such models may prove to be one of the most enduring contributions of microgenetic methods.

References

June 1991 • American Psychologist


---

June 1991 • American Psychologist

