CHAPTER 11

Microgenetic Analyses of Learning

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This chapter is based on three propositions: (1) Learning is central to child development, (2) microgenetic analyses yield unique information about learning, and (3) the information yielded by microgenetic analysis is helping to create a vibrant new field of children’s learning. The remainder of the chapter provides arguments and evidence for these three propositions, as well as describing the new field of children’s learning.

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THE CENTRALITY OF LEARNING TO CHILDREN’S DEVELOPMENT

Learning is basic to human existence in all periods of life, but it is especially so in childhood. Its centrality is now recognized even for changes that were once attributed entirely to maturation, such as the beginning of reaching, kicking, and stepping (Thelen & Corbetta, 2002). The very concept of childhood can be defined in terms of learning: Childhood is the period of life in which learning is the primary goal.

The reasoning underlying this perspective can be appreciated by contrasting the relative importance of performance and learning in adulthood to their relative importance in childhood. Adulthood is the period during which performance is primary: Adults’ success in doing their jobs, in choosing a mate, in child rearing, in deciding where to live, and even in mundane tasks such as driving has profound implications for themselves and their families. Considerable learning also takes place during adulthood, of course, but adults’ performance in the here and now is foremost. A farmer who makes unwise planting and harvesting decisions and whose crops
fail is not a successful farmer even if he learned from his less successful decisions the year before, nor is a driver successful who learned enough to improve from six traffic accidents to three from one year to the next. In contrast, a farmer who makes wise planting and harvesting decisions is successful even if he learns nothing, as is a driver who avoids all accidents but whose skill remains unchanged.

The balance between learning and performance is very different in childhood. Children have more to learn than do adults, and the capabilities they need to acquire include many that are fundamental to their future: comprehension and production of language; acquisition of fundamental concepts such as time, space, number, and mind; academic competencies such as reading, writing, and mathematics; emotional control; social interaction skills; and so on. Thus, the adage “the work of childhood is learning” embodies an important truth. In contrast, children’s absolute level of performance rarely matters in and of itself. It is unfortunate if a kindergartner lags behind in knowledge of numbers and letters, or does not work and play well with others, but the problem is serious only if it continues. A kindergartner who has made substantial progress toward catching up with her classmates in knowledge of letters and numbers or in getting along with other children, but who still does less well than most of them, has had a good year—unlike the driver who reduced his traffic accidents from six to three.

Although the process of learning always has been central within children’s development, the study of learning only sometimes has been central within the field of child development. From the 1930s through the 1960s, children’s learning was a booming area of developmental psychology. Then the area went into eclipse. A sense of the magnitude and rapidity of the shift is conveyed by the chapters on children’s learning in two successive editions of the Handbook of Child Psychology, both written by the same authority, Harold Stevenson. First consider Stevenson’s evaluation of the state of the field in the 1970 Handbook, near the end of the boom in the study of children’s learning:

> The number and quality of studies on children’s learning published each year have continued to increase.... By now there have been so many studies of children’s learning that it is impossible to review them adequately in one chapter.... Because of the vast number of publications, no attempt is made to include all possibly relevant studies. (pp. 849, 851, 852)

Now consider Stevenson’s (1983) evaluation 13 years later, after the boom ended:

> 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. (p. 213)

Indicative of this change, the length of Stevenson’s review of the literature on children’s learning decreased from 90 pages in 1970 to 23 pages in 1983. This change did not just reflect one man’s opinion. In the 1970 Handbook volume that focused on cognitive development, 10 of the 19 chapters included learning as an index entry; in the corresponding volume of the 1983 Handbook, only 2 of the 13 chapters included such an entry.

Since the publication of the 1983 Handbook, the pendulum has swung back—somewhat. On one hand, the prominence of learning within the field of developmental psychology remains far less than its prominence within children’s lives. On the other hand, the amount of research on children’s learning has increased, and the quality of this research has been high enough to create an exciting new field of children’s learning. The present chapter first provides a brief overview of the history of research on children’s learning, then examines how microgenetic methods have helped reinvigorate the area, and then examines the new field of children’s learning that is emerging.

History

Early Flowering

The rise of learning theories within developmental psychology came later than in experimental psychology and the learning theory approach never became as dominant (White, 1970). Nonetheless, learning theories were a major force in developmental psychology for many years, shaping what was studied, how it was studied, and how the results were interpreted. Many early studies of children were direct extensions of previous learning theory studies of rats, pigeons, or human adults. For example, in the 1946 edition of the Handbook, Munn’s chapter on children’s learning included the observation:

> Investigations of learning in children, rather than introducing new problems and essentially novel techniques, have followed the leads of animal and adult human
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psychology. . . In many investigations of learning inclusion of children has been merely incidental. (pp. 370, 371)

Consistent with this perspective, Munn’s chapter focused in large part on topics emphasized within the adult and animal experimental psychology of the day: conditioning, paired associate learning, motor learning, and so on.

The emphasis within the field of children’s learning on theories and methods imported from experimental psychology continued for many years. Consider the similarity between the evaluation just quoted and that of Stevenson (1970), a quarter century later:

Research on children’s learning is for the most part a derivative of psychological studies of learning in animals and human adults. Although the impetus for studying children’s learning is related to practical concerns in the educating and rearing of children, the field characteristically has been dominated by the methods and problems of the experimental psychologist. . . . The close alliance with experimental psychology has been productive. (p. 849)

It is easy to recognize these influences of learning theory on a wide variety of prominent developmental research of the 1950s and 1960s. For example, Hull’s (1943) and Spence’s (1952) approaches to discrimination learning led to the developmental research on the same topic of Kendler and Kendler (1962) and Zeaman and House (1967); the social learning approach of N. E. Miller and Dollard (1941) led to the developmental research of Bandura and Walters (1963) and Rosenblith (1959); the operant conditioning approach of Skinner (1938) led to the developmental research of Bijou and Baer (1962) and Siqueland and Lipsitt (1966); and so on. Thus, although Stevenson’s (1970) characterizations of the field of children’s learning as both derivative and productive might seem contradictory, both descriptors seem justified.

Dormancy

The withering of the field of children’s learning after 1970 reflected both its own limitations and the emergence of attractive alternatives. Learning theory emphasized simple nonverbal tasks that bore only an abstract resemblance to problems that children encounter in the world outside the laboratory. The intent was to measure basic learning processes that occur in a wide range of situations, but the tasks and experimental paradigms differed so greatly from everyday ones that it was uncertain if the learning processes used in and out of the lab shared more than a label. For example, numerous learning theory studies of concept formation required children (or adults or nonhuman animals) to choose between pairs of objects that varied in size, shape, color, and the side on which they appeared (e.g., Levine, 1966; Restle, 1962). The correct answer was whatever the experimenter said it was; the rule could be as simple as “Choose the larger one” or as complex as “Choose either a large T on the left or a small X on the right or a large X on the left or a small T on the right.” The degree of similarity between the processes used to acquire such arbitrary concepts and those used to acquire natural concepts such as “animal” or “mountain” is far from clear. In addition, the lack of ecological validity of these tasks was so extreme that it created increasing dissatisfaction with the whole learning theory enterprise among a wide range of psychologists.

Developmental psychologists also were dissatisfied for several other reasons. One was the portrayal of children as passive, inactive organisms whose learning lacked distinctive characteristics. Brown, Bransford, Ferrara, and Campione noted in their 1983 Handbook chapter that learning theories assumed that the same basic principles could be applied universally across all kinds of learning, all kinds of species, and all ages. Not surprisingly, investigators who did not believe in developmental or species differences in learning did not discover much about them. This issue was evident quite early. Munn (1946) noted, “So far as discovering anything fundamentally new concerning the learning process is concerned, the investigations on learning in children have failed” (p. 441). Although Munn recognized that this might be attributable to the tasks and procedures that were used, he concluded that “A more likely reason, however, is that the phenomenon of learning is fundamentally the same, whether studied in the animal, child, or adult” (p. 441). Some later learning theory approaches did attempt to explain developmental differences in learning (e.g., Kendler & Kendler, 1962), and their efforts attracted considerable interest for a time, but increasing numbers of developmentalists had become disillusioned with learning theory and were looking in other directions.

The marginalization of the field of children’s learning reflected not only the deficiencies of learning theories but also the emergence of attractive alternative
approaches that did not emphasize learning. The most influential alternative was Piaget’s theory, particularly as distilled in Flavell’s (1963) book “The Developmental Psychology of Jean Piaget.” Piaget’s theory was not new, of course, but Flavell’s clear and compelling presentation greatly expanded its appeal. Unfortunately, for the study of learning, Piaget (1964) drew a sharp distinction between learning and development, a distinction that relegated learning to a subordinate position. For example,

I would like to make clear the difference between two problems, the problem of development in general and the problem of learning. I think these problems are very different, although some people do not make the distinction. The development of knowledge is a spontaneous process, tied to the whole process of embryogenesis. Learning presents the opposite case. In general, learning is provoked by situations—provoked by a psychological experimenter; or by a teacher, with respect to some didactic point; or by an external situation. It is provoked, in general, as opposed to spontaneous. In addition, it is a limited process—limited to a single problem, or to a single structure. (p. 20)

It is worth noting that not all classic theorists shared Piaget’s rather dismissive attitude toward learning. Theorists such as Werner (1948, 1957) and Vygotsky (1934/1962) viewed short-term change as a miniature version of long-term change, generated by similar underlying processes and characterized by identical sequences of qualitatively distinct stages. This view is basically similar to the present perspective. However, Piaget’s theory was so dominant at the time, and his observations of age-related changes so interesting, that they shifted attention toward children’s thinking and away from their learning. This shift affected not only adherents of Piaget’s theory but critics as well. Thus, approaches that originated as alternatives to Piaget’s theory, such as core knowledge approaches (Spelke & Newport, 1998), differed in many ways from the Piagetian perspective but maintained the focus on knowledge rather than learning.

A second major influence on the field of cognitive development, information processing theories, also shifted attention away from children’s learning, though for a different reason. Information processing approaches recognized learning as a central problem and as crucial for understanding how development occurs. However, their agenda was first to describe children’s knowledge states at different ages and only then to focus on how transitions occur. This perspective is aptly captured in Simon’s (1962) suggestion,

If we can construct an information processing system with rules of behavior that lead it to behave like the dynamic system we are trying to describe, then this system is a theory of the child at one stage of development. Having described a particular stage by a program, we would then face the task of discovering what additional information-processing mechanisms are needed to simulate developmental change—the transition from one stage to the next. (p. 632)

As with Piaget’s theory, this approach led to many fascinating discoveries regarding how children think at different ages. In addition, some researchers who adopted an information-processing perspective did advance intriguing hypotheses about transition processes in cognitive development (e.g., Klahr & Wallace, 1976). In general, however, the information processing theory of the 1960s and 1970s, like Piagetian theory, shifted attention away from how children learn.

Scientific approaches create their own momentum. The intriguing findings on children’s existing knowledge generated by Piagetian, information processing, and core knowledge approaches led to many controversies. These controversies, in turn, generated new intriguing findings and new controversies regarding what children do and do not understand at particular ages, especially in infancy and the preschool period (e.g., Haith & Benson, 1998; Spelke & Newport, 1998). The development of innovative methods for studying infant cognition added to this trend, because it allowed examination of fundamental issues that could not be studied previously.

These trends produced a large body of excellent research that greatly broadened understanding of development. However, they also entailed a serious cost: an imbalanced portrayal of children that focused on static states rather than change. This tendency was evident in Piagetian, information processing, and core knowledge approaches alike; all focused primarily on skills and knowledge at particular ages rather than on the processes through which children acquired the skills and knowledge. The imbalance is understandable—knowledge states are easier to describe than change processes, and describing them is crucial for establishing the changes
that need to be explained. However, the prolonged emphasis on documenting static states resulted in a distorted description of development, one in which children appeared to spend far more time being than becoming.

**Germination**

After a period in which children’s learning received little attention, some far-sighted investigators began to envision a new field of children’s learning. For example, Brown, Bransford, Ferrara, and Campione (1983) noted the same trend toward reduced focus on learning as Stevenson (1983), but they also predicted that the metaphor of children as active organisms who devise strategies to pursue their goals would form the foundation of a new field of children’s learning. They foresaw that the study of memory for rich and varied real world content would provide a useful model for this new field, and they anticipated the emergence of several specific issues that have become central in the area. How do the characteristics of the learner, the nature of the material, and the criterion task combine to determine learning? Why do children fail to transfer useful strategies to new content? What develops to allow older children to learn many types of material more effectively than younger children?

A further insight of Brown et al. (1983) was anticipating the role that microgenetic studies would play in the resurgence of the field of children’s learning. They suggested that after documenting age-related changes in thinking, researchers would go on:

> to attack the problem of development head-on . . . by observing learning actually taking place within a subject over time. This is essentially the microgenetic approach advocated by Vygotsky (1978) and Werner (1961). . . . The revived interest in microgenetic analysis of both adult (Anzai & Simon, 1979) and children’s (Karmiloff-Smith, 1979a, 1979b) learning enables psychologists to concentrate not only on qualitative descriptions of stages of expertise but also to consider transition phenomena that accompany the progression from novice to expert status. (p. 84)

The history of the past 20 years indicates the pre-sciences of Brown et al.’s (1983) predictions. Again, changes within the *Handbook* document this trend. Learning assumed a considerably larger role in the 1998 *Handbook* than in its 1983 predecessor. M. H. Johnson (1998) noted that rather than neural development being largely prespecified, as once was assumed, the developing brain changes according to the input that it encounters; that is, the developing brain changes with learning. Aslin, Jusczyk, and Pisoni (1998) focused on how children learn to segment speech into words, and also how learning leads them to lose their early ability to discriminate some phonemic contrasts that are absent from their native language. Gelman and Williams (1998) focused on how conceptual constraints influence learning in core domains. Maratos (1998) argued that contrary to the view that people are born with a universal grammar that only requires a small amount of tuning, the remarkably idiiosyncratic and variable nature of natural grammars demands a great deal of highly specific learning. Rogoff (1998) examined how children learn through participation in socially important activities, and Klahr and MacWhinney (1998) reviewed computational models of children’s learning.

Several developments contributed to this change in *Handbook* coverage and to the more general resurgence of the field of children’s learning. One was the increasing influence of theories that see development as rising in large part out of learning. These include dynamic systems, sociocultural, and information processing theories. Such theories have motivated increasing amounts of empirical research on learning. For example, dynamic systems theory motivated researchers to examine whether acquisitions that traditionally had been viewed as a function of the child’s developmental stage, such as object permanence, could be explained by learning within the specific experimental situation, such as learning of particular arm movements and activation of particular representations. Smith, Thelen, Titzer, and McLin’s (1999) and Spencer and Schutte’s (2004) empirical demonstrations that such explanations were viable created a new way of conceptualizing object permanence.

Another important contributor to the resurgence of the field of children’s learning has been methods capable of tracing the process of learning while it occurs. Microgenetic methods in particular have made possible increasingly nuanced understanding of children’s learning. The availability of such methods, together with videocassette recorders and other useful technologies, allow theorists to raise questions about the dynamics of development that otherwise would be impossible to answer, such as what happens immediately before a child makes a discovery and whether periods of transition are accompanied by especially high variability.

Other methods are also being used to study learning. They include operant conditioning (Saffran, Aslin, &
Newport, 1996; Stokes & Harrison, 2002), elicited imitation (Bauer, Chapter 9, this Handbook, this volume), formal modeling (Munakata, Chapter 10, this Handbook, this volume), and brain imaging (Nelson, Chapter 1, this Handbook, this volume). In addition, microgenetic methods are being used to study adults’ learning (Anzai & Simon, 1979; Staszewski, 1988), as well as that of children. Limitations of space, together with the presence in this volume of the chapters by Nelson, Bauer, and Munakata, contributed to the decision to focus the present chapter on contributions of microgenetic studies to understanding of children’s learning.

MICROGENETIC METHODS FOR STUDYING LEARNING

Scientific methods and theories exert reciprocal influences. Typical cross-sectional and longitudinal methods, which sample the thinking of children at different ages, reinforce and are reinforced by theories that emphasize such questions as “By what age do children understand _____?” and “Does X develop before, after, or concurrently with Y?” In contrast, the cross sectional and longitudinal methods are less useful in testing theories that emphasize such questions as, “Through what processes do children learn _____?” and “Is Strategy X transitional to Strategy Y?” The problem is that observations of emerging competence in cross-sectional and longitudinal studies are too widely spaced to yield detailed information about the learning process. For example, a longitudinal design might involve observing children’s performance on the false belief task at 3, 4, and 5 years. The year between observations would severely limit the information that could emerge regarding the processes through which children’s understanding of false belief improves.

Essential Properties

This is where microgenetic methods are essential: for answering questions about how learning occurs. Microgenetic methods have three main properties:

1. Observations span the period of rapidly changing competence.
2. Within this period, the density of observations is high, relative to the rate of change.
3. Observations are analyzed intensively, with the goal of inferring the representations and processes that gave rise to them.

The second property is especially important. Densely sampling changing competence during the period of rapid change provides the temporal resolution needed to understand the learning process. If children’s learning usually proceeded in a beeline toward advanced competence, such dense sampling of ongoing changes would be unnecessary. We could examine thinking before and after changes occurred, identify the shortest path between the two states, and infer that children moved directly from the less advanced one to the more advanced one. Detailed observations of ongoing changes, however, indicate that such beelines are the exception rather than the rule (Siegler, 2000). Cognitive changes involve regressions as well as progressions, odd transitional states that are present only briefly but that are crucial for the changes to occur, generalization along some dimensions from the beginning of learning but lack of generalization along other dimensions for years thereafter, and many other surprising features. Simply put, the only way to find out how children learn is to study them closely while they are learning.

The logic of densely sampling changes as they occur is not unique to the microgenetic approach; the same logic underlies a number of other methods. One example is neural imaging methods such as fMRI. The dense temporal sampling of brain activity allowed by increasingly powerful magnets and software has led to many insights into the neural substrate of performance (e.g., Casey, 2001). Other neural techniques such as single cell recording are based on the same logic, as are behavioral techniques such as eye movement analysis (Just & Carpenter, 1987). In all cases, the dense sampling of performance over time allows insights into cognitive processes.

Applicability

Microgenetic designs are broadly applicable along multiple dimensions:

- **Ages of participants:** Microgenetic methods have proven useful for studying people of all ages: infants (Adolph, 1997), toddlers (Chen & Siegler, 2000), preschoolers (P. H. Miller & Aloise-Young, 1995), elementary school children (Schauble, 1996), college
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Microgenetic analyses have proven useful for studying development in highly diverse domains: problem solving (Fireman, 1996), attention (P. H. Miller & Aloise-Young, 1995), memory (Schlagmüller & Schneider, 2002), theory of mind (Flynn, O’Malley, & Wood, 2004), scientific reasoning (Kuhn, Garcia-Mila, Zohar, & Anderson, 1995), mathematical reasoning (Alibali, 1999), spoken language (Robinson & Mervis, 1998), written language (Jones, 1998), motor activity (Spencer, Vereijken, Diedrich, & Thelen, 2000), and perception (Shimojo, Bauer, O’Connell, & Held, 1986). In addition to these applications to the study of cognitive development, investigators have begun to apply microgenetic analyses to social development (e.g., Lavelli & Fogel, 2002; Lewis, 2002).

Setting: Microgenetic methods are applicable not only in laboratory settings but also in naturally occurring contexts and classrooms. For example, they have been used to study infants’ kicking and reaching in their cribs (Thelen & Corbetta, 2002), young children’s learning of narrative skills in preschool and first-grade classes (McKeough, Davis, Forgeron, Marini, & Fung, in press; McKeough & Sanderson, 1996), and fourth graders learning math skills in a collaborative learning context (Taylor & Cox, 1997). (For a review of applications of microgenetic methods to classroom research, see Chinn, in press.)

Theoretical underpinning: Microgenetic studies have proven useful for testing predictions of all of the major theories of cognitive development: Piagetian (Karniloff-Smith & Inhelder, 1974; Saada-Robert, 1992), neo-Piagetian (Fischer & Yan, 2002; McKeough & Sanderson, 1996), dynamic systems (Lewis, 2002; Thelen & Corbetta, 2002), theory (Amsterlaw & Wellman, 2004; Flynn et al., 2004), sociocultural (Duncan & Pratt, 1997; Wertsch & Hickmann, 1987), and information processing (Schlagmüller & Schneider, 2002; Siegler & Svetina, 2002). This is not coincident. Part of the reason that these approaches are viewed as major developmental theories is that they make important predictions about how change occurs. Such predictions often can be tested most precisely through microgenetic studies, in which changes are observed in detail.

Despite these large variations in age groups, content areas, settings, and investigators’ theoretical orientation, microgenetic studies of children’s learning have yielded surprisingly consistent findings. As Kuhn (2002) observed:

Although the empirical findings that microgenetic research has produced are both interesting and consequential, the single most striking thing about them is their consistency. This consistency has been maintained despite variations in methodology and despite the wide range of content areas to which the method has been applied. Consistency of this sort is unusual in developmental psychology. (p. 109)

Other reviewers of the microgenetic literature (P. H. Miller & Coyle, 1999; Siegler, 2000) have been struck by this same consistency of research findings. Ironically, it may reflect the correctness of one of the core beliefs of the earlier generation of learning theorists: More regularity may be present in how people learn than in what they know at a given age. Prominent developmental theories, such as the Piagetian, neo-Piagetian, and theory-theory approaches, have been based on the assumption that substantial regularities in thinking are present at particular ages, either across all areas of thinking or within broad domains, such as psychology or biology (Case & Okamoto, 1996; Piaget, 1952; Wellman & Gelman, 1998). The evidence for such regularities in thinking at particular ages is mixed at best (Siegler, 1996).

In contrast, the consistent findings yielded by microgenetic studies suggest that considerable regularity may be present in how children learn. This regularity in findings regarding children’s learning has been noted in reviews of studies that have not used microgenetic methods as well as in ones that have. For example, R. Gelman and Williams (1998) highlighted the importance of constraints for facilitating learning in all types of domains, both biologically privileged and nonprivileged. Similarly, Keil (1998) and Wellman and S. Gelman (1998) emphasized formation of causal connections as crucial to children’s learning in a broad range of domains. The greater regularity in studies of learning is likely due to their eliminating a number of sources of variability that limit investigators’ ability to demonstrate commonalities in thinking across different problems: differences in wording of questions, task difficulty, amount of direct experience with each task, similarity to better-understood tasks, motivational properties, and so on. Thus, yet another reason for focusing on children’s learning is that doing so promises to help overcome the fractionation of the field of developmental psychology and to identify common underlying principles.

Table 11.1 lists a number of the most consistent and important phenomena that have emerged within micro-
genetic studies of children’s learning. Each of the phenomena is discussed in some depth later in the chapter.

History

Both the name microgenetic and the idea of microgenetic designs appear to have originated with Heinz Werner (Catan, 1986). Werner (1948) hypothesized that cognitive changes over diverse time spans, ranging from milliseconds to years, include important commonalities. Therefore, in the mid-1920s, he began to perform what he labeled “genetic experiments,” that is, experiments aimed at describing the sequence of states within psychological events (this use of the term genetic, like Piaget’s description of himself as a “genetic epistemologist,” is based on the original definition of genetic as “pertaining to genes or origins.”) For example, Werner (1940) described how repeated presentation of a sequence of 12 ascending, initially indiscriminable tones eventually allowed people to form a representation in which the tones could be discriminated. Because the very rapid sequence of such mental states was believed to parallel the much slower sequence of states in development with age, the experiments were also labeled “microgenetic.” Soviet contemporaries, including Vygotsky (1930/1978), cited with approval Werner’s genetic experiments and argued for studying concepts and skills that were “in the process of change” (p. 65) rather than ones that were “fossilized” (p. 68).

Despite this promising beginning, the microgenetic method was rarely used in the ensuing years. The first spate of modern microgenetic articles appeared in the 1970s and early 1980s. Among the early adopters were Karmiloff-Smith and Inhelder (1974), Wertsch and Hickmann (1978), Karmiloff-Smith (1979b), and Kuhn and Phelps (1982). This last study was particularly important because it was the first microgenetic experiment that included all three defining features listed earlier.

Although classifications of studies as microgenetic inevitably are somewhat subjective, the prevalence of microgenetic studies clearly has increased greatly in recent years. Of the 105 studies classified as microgenetic for purposes of this review, only 10 were published before 1985. The growing frequency of microgenetic studies has several likely sources. One is the increasing emphasis on learning within prominent theories of cognitive development. Another is the increasing availability and sophistication of video recording technology and software and

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<tr>
<th>TABLE 11.1 Twenty Major Findings about Children’s Learning</th>
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<tr>
<td>1. Substantial within-child variability is present during all phases of learning and at every level of analysis: associations, concepts, rules, strategies, and so on.</td>
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<td>2. Within-child variability tends to be greatest during periods of rapid learning, though substantial variability is present in relatively stable periods as well.</td>
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<td>3. Within-child variability tends to be cyclical, with periods of lesser and greater variability alternating over the course of learning.</td>
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<td>4. Within-child variability is substantial at all ages from infancy to older adulthood.</td>
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<td>5. Initial within-child variability tends to be positively related to subsequent learning.</td>
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<td>6. Learning reflects addition of new strategies, greater reliance on relatively advanced strategies that are already being used, improved choices among strategies, and improved execution of strategies.</td>
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<td>7. Learning tends to progress through a regular sequence of knowledge states that parallel those that characterize untutored development.</td>
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<td>8. The path of learning is usually similar for learners of different ages and different intellectual levels.</td>
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<td>9. Learning often includes short-lived transitional approaches that play important roles in the acquisition of more enduring approaches.</td>
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<td>10. New approaches are generated following success as well as failure of existing approaches.</td>
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<td>11. For most types of learning, older and more knowledgeable children learn more quickly, and show greater appropriate generalization, than younger children.</td>
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<td>12. The rate of change is of human scale: faster than connectionist models imply, but slower than most symbolic models imply.</td>
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<td>13. New approaches usually are used inconsistently; discovery of new approaches tends to be the beginning of learning rather than the end.</td>
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<td>14. Once new approaches have been generated, their rate of uptake is positively related to the degree to which their accuracy is superior to that of existing approaches.</td>
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<td>15. The breadth of change also is of human scale, including everything from instantaneous to extremely gradual generalization.</td>
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<td>16. The likelihood of choosing any given approach can be increased either by increasing the strength of that approach or by weakening the strength of competing approaches.</td>
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<td>17. Causal understanding plays a crucial role in learning.</td>
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<td>18. Requests to explain observations often promote learning above and beyond the effects of feedback and practice.</td>
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<td>19. The mechanisms underlying the effects of explanatory activity include increased likelihood of learners generating any explanation, increased persistence of explanatory efforts, and diagnosis and repair of flaws in mental models.</td>
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<td>20. Learning often proceeds with little or no trial and error; conceptual understanding often allowing children to reject inappropriate strategies without ever trying them.</td>
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hardware tools that allow faster extraction of information than was possible until recently. A third is the increasingly broad range of tasks for which precise age norms have been established, thus setting the stage for microgenetic studies.

Probably the most important reason for the increased prevalence of microgenetic methods, however, is that it has become apparent that the value of the precise data on cognitive change that microgenetic designs yield more than offsets the time and effort required to obtain the data. Consider how the data obtained in microgenetic studies have allowed investigators to address one fundamental issue: how children discover new strategies. Microgenetic methods, unlike other developmental designs, allow identification of the exact trial on which each participant first used the new approach. Identifying the trial on which a new approach was first used allows examination of the nature of the discovery: whether a child was excited about the innovation, whether the child was even aware of having used a new approach, and whether or she could explain why the new approach was advantageous. Knowing exactly when the new approach was first used also allows examination of performance just before the discovery: what types of problems preceded the discovery, whether the child failed to solve the immediately preceding problems, whether the child was taking an unusually long time to solve those problems, and so on. Moreover, knowing when the discovery was made allows examination of performance just after the discovery: how consistently the child used the new strategy on the same type of problem, how broadly the child generalized the new strategy to other types of problems, how efficiently the child executed the new strategy, and how all of these dimensions of performance changed as the child gained experience with the new approach. These are the benefits that are leading increasing numbers of investigators to use the microgenetic approach to study children’s learning.

Methodological Issues

Microgenetic studies raise a variety of methodological issues, including ones of experimental design, strategy assessment, and data analysis.

Issues of Experimental Design

Because microgenetic studies generally require coding strategy use or other units of behavior on a great many trials, the distribution of experimental designs used in such studies differs from the overall distribution of experimental designs in the field. Quite a few microgenetic studies employ single subject designs, either with or without instruction (e.g., Agre & Shrager, 1990; K. E. Johnson & Mervis, 1994; Schoenfeld, Smith, & Arcavi, 1993). In one such case, Lawler (1985) described his daughter’s learning of how to debug simple computer programs, solve simple arithmetic problems, and play tic tac toe over 90 sessions during a 4-month period. In another such study, Robinson and Mervis (1998) analyzed Mervis’ son’s acquisition of grammatical and lexical forms over almost 400 sessions over 13 months.

Another common type of microgenetic design involves focusing on the learning of a relatively small number of participants over a substantial period without any experimental intervention (e.g., Saada-Robert, 1992; Thelen & Ulrich, 1991). For example, Spencer et al. (2000) observed four infants’ reaching in a free-play situation twice per week between 3 and 30 weeks of age and every other week between 32 and 52 weeks of age. Shimojo et al. (1986) study of 16 infants’ acquisition of binocular depth perception over 31 weekly sessions between 1 and 8 months is another example. Thus, microgenetic methods can be applied to studying change over relatively long as well as relatively short time periods, and to study changes that might be described as “developmental,” because they do not involve explicit experimental interventions, as well as changes that do involve such interventions and thus are more prototypic of “learning studies.”

A third common microgenetic design involves presenting children with an unusually high density of an experience, with the goal of speeding up the typical developmental process, thus allowing more detailed analysis of change than would otherwise be possible (e.g., Siegler & Jenkins, 1989). This type of design, like the first two, does not include a control group, because the focus is on the way in which the change occurs rather than on establishing the effectiveness of the experience relative to changes that might have happened anyway. Examples of this design include Karmiloff-Smith’s (1979b) study of changes within a single session in children’s drawing of route maps, Kuhn, Schaulbe, and Garcia-Mila’s (1992) study of changes in 10-year-olds’ learning of scientific experimentation skills over 18 sessions in a 9-week period, and Schlagmüller and Schneider’s (2002) study of changes in 9- and 11-year-olds’ organization of pictures of objects on a sort-recall task in nine experimental sessions over an 11-week period.
Pressley (1992) criticized these three types of microgenetic designs by arguing that without a control group, they were subject to a variety of sources of experimental invalidity. However, it often is unclear what an appropriate control group would be in such studies, given that the focus is on describing how changes occur under the particular experimental condition, rather than on contrasting how different experimental conditions influence behavior. In addition, the studies have yielded fine-grain data about acquisition of complex skills, concepts, and domains, data that would have been unlikely to have been obtained in any other way and that have contributed a great deal to understanding of learning.

Moreover, despite Pressley’s concern that the demands of microgenetic methods inherently preclude use of true experimental designs, increasing numbers of microgenetic studies have employed them (e.g., Chen & Siegler, 2000; Church, 1999; Siegler & Stern, 1998). For example, Alibali (1999) randomly assigned third and fourth graders to one of five experimental groups to compare learning about mathematical equality under varying conditions, and Klahr and Chen (2003) randomly assigned 4- and 5-year-olds to one of two groups to contrast learning about indeterminacy under the alternative conditions.

Although his claim that microgenetic methods preclude true experimental designs proved incorrect, Pressley (1992) did identify a number of tradeoffs that shape microgenetic research—tradeoffs among number of participants, number of sessions, sampling density, and type of task. Some of these tradeoffs are fairly obvious, but others are quite subtle.

One obvious tradeoff is that between number of participants and number of sessions. Microgenetic studies have included from 1 to more than 300 sessions and from 1 to more than 150 participants. In general, the greater the number of sessions, the smaller the number of participants. To cite the extremes, Robinson and Mervis (1998) observed one child for more than 300 sessions, whereas Alibali (1999) observed 178 participants for a single session.

Both number of participants and number of sessions trade off with density of observations. Microgenetic studies have involved within-trial analyses (e.g., Coyle & Bjorklund, 1997; Graham & Perry, 1993), trial-by-trial analyses (e.g., Blöte, Resing, Mazer, & Van Noort, 1999; Siegler & Jenkins, 1989), and session-by-session analyses (Jones, 1998; Shimojo et al., 1986). As a general rule, the higher the rate of change of the phenomenon under the experimental conditions, the higher the density of observations needs to be. The demands of high-density observation militate toward either a small number of participants, a small number of sessions, or both.

All of these variables also trade off in a rather nonintuitive way with the prevalence of the task in the everyday environment. Some microgenetic studies present everyday tasks that children have encountered but not mastered; other studies present novel tasks. Similarly, some studies present tasks under more typical circumstances than other studies. Although it may seem surprising, changes on familiar tasks presented under quite natural circumstances tend to occur more slowly than changes on novel tasks presented under conditions that are by definition novel. For example, studies of everyday tasks, such as reaching (Thelen & Corbetta, 2002) and arithmetic (Siegler & Jenkins, 1989) have generally reported quite slow rates of change, whereas studies of novel tasks such as Tower of Hanoi (McNamara, Berg, Byrd, & McDonald, 2003) and number conservation (Church & Goldin-Meadow, 1986) have generally reported more rapid changes. Presumably, on familiar tasks most children have already made the easiest discoveries, so that the remaining ones tend to require more time or more facilitative conditions. Thus, although ecologically valid tasks and conditions might be expected to elicit more rapid change than novel tasks and circumstances, the opposite tends to be true.

One way of minimizing these trade-offs is by applying multiple methods, with different sets of advantages and disadvantages, to the same task. This approach has been used to good advantage in the study of semantic organization strategies. By combining cross sectional and longitudinal studies with microgenetic studies, Schneider and his colleagues were able to establish that changes occurred considerably more rapidly than suggested by the cross-sectional data (Schneider, Kron, Hünnerkopf, & Krajewski, 2004; Schlagmüller & Schneider, 2002).

**Issues of Strategy Assessment**

A second class of methodological issues raised by microgenetic studies involves the reliability and validity of trial-by-trial strategy assessments. Although neither limited to microgenetic studies nor invariably used in them, trial-by-trial assessments are fundamental to many microgenetic studies. Precise analyses of strategy discoveries, of generalization of new strategies beyond their initial context, and of the precursors of discoveries...
require identification of when the strategy first emerges. This emergence can be specified most precisely through trial-by-trial assessments.

Before discussing issues of trial-by-trial assessment of strategies, however, it is necessary to define the term strategy. The present definition of strategy is one that was first advanced by Siegler and Jenkins (1989, p. 11): a “procedure that is nonobligatory and goal directed.” This definition distinguishes strategy from procedure, in that some procedures are obligatory (they are the only way to achieve the goal). The definition also distinguishes strategy from behavior, in that behaviors do not imply any particular goal. Finally, the definition does not imply a rational generation process, conscious choice, or reportability. Including such criteria would exclude many activities that can profitably be conceptualized and analyzed within the present framework, as well as raising truly thorny issues, such as deciding what constitutes a rational generation process.

Returning to issues of assessment, the desirability of assessing strategy use on a trial-by-trial basis has shaped microgenetic research in several ways. Perhaps the most striking influence is that it has led researchers to rely on tasks that involve substantial overt behavior: crawling, walking, reaching, and stepping (e.g., Adolph, 1997; Thelen & Corbetta, 2002); writing and telling stories (Jones, 1998; Jones & Pellegrini, 1996; McKeeough & Sanderson, 1996); manipulating physical apparatuses, such as gear systems, bridges, and robots (Dixon & Bangert, 2002; Granott, 1998; Parziale, 2002; Perry & Lewis, 1999; Thornton, 1999); doing mathematics (Blöte et al., 2004; Fletcher, Huffman, Bray, & Grupe, 1998; Goldin-Meadow & Alibali, 2002; Grupe, 1998); organizing to-be-remembered pictures or objects (Blöte et al., 1999; Coyle & Bjorklund, 1997; Schlagmüller & Schneider, 2002); and solving problems collaboratively (Ellis, 1995; Granott, Fischer, & Parziale, 2002; Wertsch & Hickmann, 1987) among them. The possibilities created by trial-by-trial analysis also have influenced choices of dependent measures. Instead of relying solely on accuracy or solution times, researchers who conduct microgenetic studies also tend to assess the strategy used on each trial through use of videotapes of ongoing behavior, immediately retrospective verbal reports, notebooks that document scientific observations and conclusions, and other external indicators of thinking. This reliance on audible and visible behavior to infer thought processes is atypical of cognitive developmental research (though the reasons for other types of research not making greater use of these external manifestations of thinking are unclear).

Microgenetic studies of children 4 years and younger have usually relied entirely on overt behavior to assess strategies. This approach has been followed, for example, in studying infant motor development (Adolph, 1997; Vereijken & Thelen, 1997), toddlers’ problem solving (Chen & Siegler, 2000), and 3- and 4-year-olds’ counting, memory, and attentional strategies (Bjorklund, Coyle, & Gaultney, 1992; Blöte et al., 2004; P. H. Miller & Aloise-Young, 1995).

Some studies of older children also have relied entirely on overt behavior to assess strategies (e.g., Bray, Huffman, & Fletcher, 1999; Lemaire & Siegler, 1995). However, in most recent studies of children 5 years and older, researchers have based strategy assessments on a combination of overt behavior and verbal reports provided during performance or (typically) immediately after. In most studies, the overt behavior is the basis of classification on trials on which it provides unambiguous evidence of which strategy was used; the verbal reports are used on trials on which overt behavior is absent or ambiguous. The combination of overt behavior and verbal reports has proved applicable for assessing strategy use on a wide range of tasks and among diverse populations, for example children with learning disabilities (Ostad, 1997).

Although use of verbal reports to infer strategy use has been widespread, the practice also has been questioned. Concerns have been raised about the veridicality and reactivity of such reports, with some investigators arguing that the need to generate verbal reports affects strategy use and other aspects of performance (Cooney & Ladd, 1992; Russo, Johnson, & Stephens, 1989). The data on which these criticisms were based, however, came from studies that lacked criteria of strategy use independent of the verbal reports (Bray et al., 1999). Results from studies that have included measures of strategy use independent of verbal reports (e.g., solution times, observations of overt behavior) have led to much more optimistic conclusions regarding the value of using verbal reports along with overt behavior.

Veridicality. The most basic issue regarding verbal reports is whether the assessments yielded by using them are accurate. Ericsson and Simon (1984) reviewed the literature on this issue and concluded that retrospective reports generally are veridical when (a) the verbal report is obtained while the trace of processing activity
remains in short-term memory, (b) the processes being described are of sufficient duration (roughly 1 second) that they produce a symbol in working memory, and (c) the processes are relatively easy to describe.

Since the publication of Ericsson’s and Simon’s seminal book, a great deal of evidence has supported their conclusion (Crutcher, 1994; K. M. Robinson, 2001; Siegler, 1987, 1989). In particular, among 5-year-olds and older individuals, classifying strategy use for each participant on each trial on the basis of both overt behavior and immediately retrospective self-reports has been found to increase the accuracy of classifications relative to that possible through classifying each participant’s strategy use solely on the basis of overt behavior (Siegler, 1996).

To illustrate the type of data on which this conclusion is based, consider one study that tested whether examining immediately retrospective verbal reports as well as ongoing overt behavior results in more accurate strategy assessments than relying on the overt behavior alone (McGilly & Siegler, 1990). This study investigated 5- to 9-year-olds’ serial recall strategies under verbal-report and no-verbal-report conditions. Children in the verbal-report condition were asked on each trial to describe what, if anything, they had done to help them remember; children in the no-verbal-report condition were not asked about their strategy use but were otherwise treated identically. A variety of measures indicated that the verbal reports added to the validity of the strategy assessments. In particular, the verbal reports revealed considerably more use of repeated rehearsal than was evident without them (74% versus 47% of trials), and did not bias the children’s behavior (as indicated by the amount and types of visible strategy use being highly similar in verbal-report and no-verbal-report conditions). Bray et al. (1999), obtained similar findings with retarded children on a different memory task. Thus, for children 5 years and older on tasks that meet the criteria described by Ericsson and Simon (1984), examining verbal reports as well as overt behavior on each trial increases the accuracy of strategy assessments over that possible from examining overt behavior alone.

Reactivity of Self-Reports. The above-cited finding of McGilly and Siegler (1990) that overt strategy use was essentially identical regardless of whether verbal reports were requested provided some evidence that requests for self-reports of strategy use do not alter the strategies that children use. Results of other studies and from other measures also indicate that immediately retrospective verbal reports are usually nonreactive. For example, Bray et al. (1999) and Robinson (2001) found that requests for such verbal reports had no effect on accuracy and also did not affect the frequency of use of overt strategies on organizational memory and arithmetic tasks.

To minimize the possibility of reactivity, it is essential to avoid instructions that bias participants in favor of one strategy or another; such biased instructions can have large effects on strategy use (Kirk & Ashcraft, 1997). With that caveat, however, it appears that trial-by-trial strategy assessments, based on both observations of ongoing behavior and immediately retrospective verbal reports, can provide veridical and nonreactive strategy assessments for 5-year-olds and older individuals.

Issues of Data Analysis

Investigating change introduces a variety of complex issues regarding data analysis, issues sufficiently difficult that a number of methodologists have argued that no good inferential statistical solution exists for many problems at present (Willett, 1997). These analytic complexities have led to a greater reliance on graphical techniques than is typical in developmental research as a whole and also the use of several inferential statistical techniques that are specialized for analysis of change. Two techniques that have proven particularly useful in microgenetic research are presented here; for more comprehensive discussions see Allison (1984), Singer and Willett (2003), Collins and Sayer (2001), and Moskowitz and Hershberger (2002).

Graphical Techniques. Microgenetic studies often rely heavily on graphical presentation of data. Such graphical analyses have been particularly common in portrayals of discrete aspects of change, for example discovery of new strategies. One graphical technique that has proven especially revealing for examining discrete aspects of change is backward trial graphing. This is a technique in which the event of interest for each participant is aligned with the zero point on the X-axis, regardless of when it occurred in the sequence of trials. In almost all cases, the event of interest occurs for different participants on different trials. Thus, one participant’s zero point might occur on the 10th trial of the experiment, another on the 20th, and another on the 30th. All other points on the X-axis are defined relative
to the zero point. The −1 trial or trial block is defined as the one immediately before the event of interest, the −2 trial or trial block is defined as the one immediately before that, the +1 trial or trial block is defined as the one immediately after the event of interest, and so on. Thus, backward trial graphs reveal what led up to the event of interest and what happened immediately after it.

The way in which this graphical technique has been used to illuminate change processes within microgenetic studies can be illustrated by describing its use in a study that examined whether unconscious discoveries sometimes precede conscious ones (Siegler & Stern, 1998). Second graders were presented problems of the form, A + B = C (e.g., 18 + 5 = _). These problems were of special interest for investigating unconscious discovery because they could be solved by different strategies that implied very different solution times. The computation strategy, which involved adding the first two numbers and then subtracting the third, implied long solution times, because the computations take young children considerable time. In contrast, the shortcut strategy, which involved reasoning that because B − B = 0, the answer must be A, could be executed much more quickly, because no computation was required.

This logic was borne out by the data; the mean reaction time (RT) when children used the computation strategy (as indicated by overt behavior and verbal report) was 16 seconds, whereas the mean RT when they used the shortcut strategy was 3 seconds. Especially important, there was virtually no overlap in solution times; almost all times were either 8 seconds or more, indicating use of computation, or 4 seconds or less, indicating use of the shortcut strategy. This fact, together with the fact that the second graders who participated invariably started out using computation, allowed unusually direct examination of unconscious strategy discovery. In particular, if children’s solution times suddenly declined from the computation range to the shortcut range, but the children continued to report using the computation strategy, then it could be inferred that they had discovered the shortcut at an unconscious level (an approach labeled the “unconscious shortcut strategy”).

The predicted data pattern was observed. Children’s solution times dropped from an average of 12 seconds on the three trials just before their first use of the unconscious shortcut to an average of less than 3 seconds on the first trial on which they used the unconscious shortcut. This finding motivated use of backward trial graphs to examine children’s discoveries in more detail.

Figure 11.1 includes two backward trial graphs, which show the patterns of strategy use leading up to the first use of the unconscious shortcut (left) and the first use of the conscious shortcut (right). As shown in the graph on the left, before children’s first use of the unconscious shortcut, they consistently used the computation strategy. After the initial use of the unconscious shortcut, most children continued to use the unconscious shortcut over the next three trials. By the fourth trial after the initial use of the unconscious shortcut, half of the children were conscious of using the shortcut (as indicated by their verbal reports).

The graph on the right shows a parallel backward trial graph centered on children’s first conscious use of the shortcut. On each of the three trials immediately preceding the first conscious use of the shortcut, roughly 80% of children used the unconscious shortcut (as opposed to less than 10% use of this strategy for the study as a whole). Once children began to report using the shortcut, they continued to use it quite consistently for the rest of that session (though most forgot and needed to rediscover it in the next session a week later). As this example illustrates, backward trial graphing procedures can reveal in considerable detail the events surrounding strategy discovery and other events of interest.

Inferential Statistical Techniques. Inferential statistical techniques for analyzing the type of categorical, repeated measures, nonlinear patterns of data typically yielded by microgenetic studies are not as well developed as techniques based on the general linear model, such as regression and ANOVA. However, some inferential statistical techniques are specifically useful for analyzing microgenetic data. One such class of statistical approaches is collectively labeled “event history analysis” (Allison, 1984; Singer & Willett, 2003). This class of techniques has been used most widely to analyze the type of one-time events that interest epidemiologists (e.g., death). However, the techniques are equally applicable to one-time events of interest to psychologists, such as discovery of a new strategy or walking unaided for the first time. Moreover, event history analysis can also be applied to events that occur multiple times. The technique is particularly useful because it allows examination of time-dependent predictor variables, such as mean solution time on the previous N trials, and because it handles in a nonarbitrary way cases in which the event of interest fails to occur during the study (right censored

Moreover, it yields results that can be interpreted like the results of standard regression techniques.

In explaining the applicability of event history analysis to microgenetic data, Dixon and Bangert (2002) noted the centrality of two concepts: the risk set and the hazard rate. The risk set includes all participants who have not yet experienced the event of interest, for example those who have not yet generated a strategy. This set decreases over the course of the experiment, as more participants experience the event of interest. The hazard rate is the probability of an event occurring on a given trial; calculation of this probability must reflect the risk set on that trial. For dichotomous variables such as strategy discovery, logistic regression can be used to determine which variables influence the hazard rate.

Dixon and Bangert (2002) used event history analysis to examine discovery of strategies for solving gear movement problems. To determine the relation of prior performance to the likelihood of discovery, they examined speed and accuracy of solutions both on all preceding trials and on a moving window of the immediately preceding five trials. Solution times on the five previous trials, though not on all trials, predicted discovery; the longer the solution times on those recent trials, the more likely that children would discover a new strategy. This predictive relation held true for two different advanced strategies. The event history analysis also revealed that other aspects of recent past performance, including inaccuracy and low rate of guessing, were positively related to the likelihood of discovery. Thus, techniques such as event history analysis and backward trial graphing are useful for analyzing microgenetic data.

OVERLAPPING WAVES THEORY

Microgenetic studies have consistently indicated that children’s thinking is more variable than recognized within most theories of cognitive development. Different children use different strategies; individual children use different strategies on different problems within a single session; individual children often use different strategies to solve the same problem on two occasions close in time; and so on (Siegler, 1996).

To capture these and other findings, Siegler (1996) proposed overlapping waves theory. Perhaps because this theory co-evolved with microgenetic methods, it has
The overlapping waves model.

Proven particularly useful for integrating findings from such research.

The basic assumption of overlapping waves theory is that development is a process of variability, choice, and change. As illustrated in Figure 11.2, the theory posits that children typically know and use varied strategies for solving a given problem at any one time. With age and experience, the relative frequency of each strategy changes, with some strategies becoming less frequent (Strategy 1), some becoming more frequent (Strategy 5), some becoming more frequent and then less frequent (Strategy 2), and some never becoming very frequent (Strategy 3). In addition to changes in relative use of existing strategies, new strategies are discovered (Strategies 3 and 5), and some older strategies abandoned (Strategy 1).

In many cases, several of these patterns are evident within a single study. Consider a study of number conservation (Siegler, 1995) in which 5-year-olds were given a pretest and four learning sessions. During the learning sessions, children needed to explain the logic underlying the experimenter’s answer on each trial. As shown in Figure 11.3, over the course of the experiment, reliance on the relative lengths of the two rows of objects decreased, reliance on the type of transformation that had been performed increased, reliance on counting stayed at a constant low level, and answering “I don’t know,” first increased and then decreased. Interestingly, roughly half of the 5-year-olds first used the most advanced type of reasoning, reliance on the type of transformation, on a pretest trial. For these children, learning involved increased reliance on transformational reasoning; for the others, it involved discovery of the new approach as well as increasing reliance on it.

As this example illustrates, an important feature of overlapping waves theory is that it provides a means of integrating qualitative and quantitative aspects of learning within a single framework. The approach recognizes that children discover qualitatively novel strategies and concepts; it also recognizes that much of development is due to quantitative shifts in the frequency and efficiency of execution of strategies, and in the adaptiveness of choices among them. Learning clearly involves both qualitative and quantitative changes; there is no reason for developmental theories to focus on one to the exclusion of the other.

Overlapping waves theory also makes several assumptions that are not evident in Figure 11.2. 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. A related assumption is that such choices among alternative approaches generally become even more adaptive with experience in the content area. For example, from the beginning of their
experience with ramps, toddlers adjust their descent strategies to the steepness of the ramp (Adolph, 1997). They use quicker but riskier strategies on the shallower ramps and slower but surer strategies on the steeper ones. With age and locomotor experience, their descent strategies become even more finely calibrated to the ramp’s slope. A further assumption is that improvements in performance during childhood reflect a combination of generation of superior new approaches; greater reliance on relatively advanced approaches that are already known; increasingly adaptive choices among approaches; and improved execution of all approaches.

Of particular importance for the present discussion, overlapping waves theory suggests that cognitive change can be analyzed along five dimensions: source, path, rate, breadth, and variability. The source of change refers to the causes that set the change in motion. The path of change is the sequence of knowledge states, representations, or predominant behaviors that children use while gaining competence. The rate of change concerns how much time or experience separates initial use of a new approach from consistent use of it. The breadth of change involves how widely the new approach is generalized to other problems and contexts. The variability of change refers to differences among children in the other dimensions of change, as well as to the changing set of strategies used by individual children.

To see how change can be analyzed in terms of these dimensions, again consider the Siegler (1995) study of number conservation. The source of the most dramatic change in this study was a combination of feedback on the correctness of answers and requests that the 5-year-olds explain why the correct answer (which had been indicated by the experimenter) was correct. This combination led to greater learning than feedback alone. The path of change involved children who were asked to explain the experimenter’s reasoning initially relying most often on the relative length of the rows, then going through a period in which they abandoned this approach but did not adopt any consistent alternative, and then usually adopting the correct approach of relying on the type of transformation that the experimenter had performed. The rate of change was moderate; most children required several sessions to progress from initial use to consistent use of the transformational strategy. The breadth of change was relatively narrow; even some of the best learners in the study continued in the final session to often advance length explanations (rather than transformational ones) of the experimenter’s reasoning on problems on which the longer row also had more objects. Finally, there was substantial variability both within and between children. At the level of within-child variability, only 2% of children relied on a single strategy throughout the study; 70% of children used three or more approaches. At the level of between-child variability, individual differences in learning could be predicted by two pretest measures: total number of strategies used by the child and whether the child ever used two different strategies on the same problem. Thus, distinguishing among the source, path, rate, breadth, and variability of change provided a useful framework for analyzing children’s learning.

The remainder of this chapter uses the five dimensions of change specified by overlapping waves theory to examine the new field of children’s learning and how microgenetic studies have contributed to it. The conclusions are based on 105 studies that met at least one of three criteria for being microgenetic. One criterion was self-description; I attempted to include all studies whose authors used the term microgenetic in the title or abstract (as indicated by a PsychLit search undertaken when I started to write the review) and that focused on children’s learning. A second criterion was identification in prior reviews; I attempted to include studies that were described as microgenetic in one of three previous reviews of the literature: Siegler and Crowley (1991), Kuhn (1995), and P. H. Miller and Coyle (1999). A third criterion was meeting the three definitional standards for microgenetic designs, regardless of whether the authors or previous reviewers labeled them “microgenetic.”

A few caveats are in order. The boundaries of the category “microgenetic studies” are inherently somewhat subjective, and either narrower or broader criteria could have been adopted. For example, studies that examined pretest-posttest changes, but not the intervening change process, were excluded on the logic that they did not allow detailed, data-based specification of the representations and processes that led to learning. For the same reason, studies that did not present quantitative analyses of changing competence, or that only examined changes in percentage of correct answers rather than also examining changes in strategy use, were excluded. Good arguments certainly could be made for other inclusion criteria that would have resulted in broader, narrower, or overlapping coverage with that in the present review. Even within the present criteria, studies that fit have almost certainly been inadvertently omitted. However, the studies that were examined provide a good sampling of results that have emerged from microgenetic studies of children’s learning.
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THE NEW FIELD OF CHILDREN’S LEARNING

The findings yielded by microgenetic studies are organized in terms of their implications for the five dimensions of learning described: variability, path, rate, breadth, and source. The discussion of each dimension begins with a summary of basic findings, then examines influences of child and environment on that dimension, and concludes with a discussion of implications and unresolved questions.

Variability

Perhaps the single central phenomenon that has been revealed by microgenetic studies is the great variability of learning (Granott, 2002; Kuhn, 1995; Lee & Karmiloff-Smith, 2002; P. H. Miller & Coyle, 1999; Siegler & Crowley, 1991). Such variability is especially evident in microgenetic studies, because the trial-by-trial assessments characteristic of the approach reveal different processing approaches within as well as between individuals. The variability is evident at every level of analysis. It is present in all domains, not just motor activities and memory where it has long been recognized, but in higher cognitive processes, such as problem solving, reasoning, and conceptual understanding, as well. It is present not only during delimited transitional periods, where it has long been recognized, but in periods where change is less rapid. It is present, moreover, not just at the neural and associative levels, where it has long been recognized, but also at the level of rules, strategies, theories, and other units of higher-level cognition. Finally, the variability is present not only between different people, but also within a single person solving the same problem at two points close in time and even within an individual’s actions on a single trial. This section presents evidence for this pervasive variability and for how the variability is related to learning.

Basic Empirical Phenomena

Within-Child Variability

Massive variability of thought and action characterizes people of all ages. It is characteristic of infants; for example, Adolph (1997) found that in descending down ramps, 5- to 15-month-olds sometimes crawled, sometimes slid on their belly, sometimes slid on their behind, sometimes slid head first, sometimes slid feet first, sometimes descended in a sitting position, and sometimes refused to go down at all. It was not the case that one baby used one approach and a different baby another; on relatively shallow slopes, each baby used an average of five distinct strategies, and on relatively steep slopes, each baby used an average of six (Adolph, 1997; Wechsler & Adolph, 1995).

Toddlers’ thoughts and actions are similarly variable. Chen and Siegler (2000) found that 18- to 35-month-olds who needed to select an appropriate tool to pull in a desirable toy sometimes used a tool, sometimes reached with their hands, sometimes requested their mother’s help, and sometimes just sat and stared at the toy, perhaps hoping that someone would help them. Among the toddlers, 74% used at least three of these strategies during the 13 trials of the experiment, and only 3% used a single strategy throughout.

Comparable variability has been found in microgenetic studies of preschoolers. Most 3- and 4-year-olds use multiple selective attention strategies (P. H. Miller & Aloise-Young, 1995); most 4-year-olds use multiple strategies to solve analogy problems (Tunteler & Resing, 2002); most 4- and 5-year-olds use multiple arithmetic strategies (Siegler & Jenkins, 1989); and so on.

Older children’s and adults’ strategies are similarly variable. For example, Alibali (1999) found that third and fourth graders used six incorrect strategies and four correct strategies in both speech and gesture while solving mathematical equality problems. Kuhn, Schaubel, and Garcia-Mila (1992) found that fifth graders changed their minds about the causal status of features in a scientific reasoning context an average of 10 times; in another study that used a similar task, fifth graders and adults changed their mind about the causal status of features an average of 14 times (Schauble, 1996). Variability of spelling strategies is similarly variable; in Kwong and Varnhagen (in press), each of four strategies was used by a majority of first graders, and each of seven strategies was used by a majority of adults. Thus, thought and action are highly variable within individual infants, toddlers, children, and adults.

This trial-to-trial variability in strategy use is not attributable to people moving in an orderly progression from less adequate strategies to somewhat more adequate strategies to yet more adequate strategies over the course of an experiment. Children often use more-advanced approaches on one trial and then regress to less-advanced ones on the next (Blöte, Van Otterloo, Stevenson, & Veenman, 2004; Coyle & Bjorklund, 1997; Kuhn & Phelps, 1982; Tunteler & Resing, 2002). Illustratively, P. H. Miller and Aloise-Young (1995) found
that 41% of changes in information gathering strategies from one trial to the next were regressions from more advanced to less advanced approaches. These regressions are temporary—the longer trajectory of change was upward in all of these studies—but the progress reflects a back and forth competition rather than a steady march forward.

The trial-to-trial variability cannot be explained in terms of children using different strategies on different problems. The variability is present even when the same problem is presented twice, relatively close in time. These changes, like those on successive trials, often reflect surprisingly even balances between improvements and regressions in situations in which children are not given instruction. Siegler and Shrager (1984) found that 45% of changes of level of basic addition strategies were in a negative direction, and Siegler and McGilly (1989) found that 43% of changes of level of time telling strategies were in a negative direction. In these cases and others, progressions outnumber regressions, but the difference is smaller than might have been expected.

The trial-to-trial variability also is not limited to tasks on which the two strategies differ in efficiency but not in their logical quality. Children have been found to show regressions from logically superior strategies to logically inferior ones surprisingly often. Such regressions have been found on numerous tasks that allow logically superior and inferior strategies, including mathematical equality (Alibali, 1999), matrix completion (Siegler & Svetina, 2002), number conservation (Church & Goldin-Meadow, 1986), control of variables (Schauble, 1990), and logical inference (Kuhn et al., 1992). Adults in the same studies have been found to regress from more advanced to less advanced logic on the last three of these tasks as well. For example, adults as well as children often generate valid inference forms in reasoning about causality and then regress to invalid forms of reasoning (Kuhn et al., 1995). Even Charles Darwin frequently regressed from more to less advanced thinking about evolution, as reflected in the reasoning in his notebooks (Fischer & Yan, 2002).

Cognitive variability also has been demonstrated within a single trial. The most extensive demonstrations of this phenomenon have come from research on gesture-speech mismatches (Alibali & Golden-Meadow, 1993; Church & Goldin-Meadow, 1986; Graham & Perry, 1993; Perry & Lewis, 1999). On a variety of tasks, including number conservation, mathematical equality, and gear motion, children frequently express one strategy in speech but a different strategy in gesture. For example, in Church’s (1999) conservation study, 53% of children generated gesture-speech mismatches on at least three of the six problems. When such mismatches occur, children typically express more advanced understanding in gesture than in speech; for example, they might simply cite the height of the liquid columns in explaining their reasoning about liquid quantity conservation, but their hand gestures might include both vertical motions comparing the heights of the two liquid columns and horizontal motions comparing their cross-sectional areas.

A variety of other types of within-trial variability have also been documented. On sort/recall memory tasks, children often use multiple strategies on a single trial, such as first organizing the objects into groups and then rehearsing either the names of the groups or the names of the items within each group (Coyle & Bjorklund, 1997; Schlagmüller & Schneider, 2002). On number conservation problems, children sometimes explain their reasoning in terms of both the length of the rows and the type of transformation on items where the two lead to the same answer (Siegler, 1995). On gear problems, children fairly often advance an explanation and follow it with second thoughts, such as, “Wait a minute, I made a mistake” (Perry & Lewis, 1999).

Significance of Within-Child Variability
The fact that substantial within-child variability exists does not necessarily mean that such variability is important. Traditional approaches have recognized the existence of within-subject variability but have treated it as a nuisance to be minimized—error variance (van Geert, 2002). Microgenetic studies, however, have revealed that within-child variability is important—for predicting change, for analyzing change, and for understanding change mechanisms.

Significance for Predicting Change. High initial variability of strategy use often predicts substantial later learning. This relation has been documented with numerous types of variability in numerous content areas. Number of strategies used by each child on a pretest has been found to correlate positively with the child’s subsequent learning on number conservation and sort-recall tasks (Coyle & Bjorklund, 1997; Siegler, 1995). Number of strategies used by each adult on a pretest has been found similarly predictive of the adult’s subsequent learning on gear problems (Perry & Elder, 1997). In addition, children’s use of multiple strategies on a single trial (as opposed to over the entire set of
problems) has been found predictive of their learning on mathematical representation problems (Fujimura, 2001), on taxonomic memory problems (Schlagmüller & Schneider, 2002), and on number conservation problems (Siegler, 1995). The number of different explanations and the number of arguments that a child advances in support of a given explanation on conservation problems also has been found to predict the child’s learning (Church, 1999). In addition, progressing through a variable state, in which gestures and speech express different understandings, has been found predictive of generalization to a novel task (Goldin-Meadow & Alibali, 2002).

Positive relations between initial variability and subsequent learning have emerged not only regarding the variability of what children say but also the variability of how they say it. Pauses, vagueness, false starts, talking to oneself, tapping the table, and verbal disfluencies all have been demonstrated to be positive predictors of learning (Bidell & Fischer, 1994; Caron & Caron-Pargue, 1976; Hosenfeld, van der Maas, & van den Boom, 1997; Siegler & Engle, 1994; Siegler & Jenkins, 1989). For example, in Graham and Perry (1993), 64% of children who produced vague pretest explanations for answers to mathematical equality problems succeeded on posttest and transfer problems, versus 23% of children who produced more specific explanations.

To specify the influence of different types of verbal variability, Perry and Lewis (1999) presented fifth graders with gear movement problems and obtained independent measures of four types of variability during children’s verbal protocols: long pauses, false starts, omissions of nouns or verbs (a form of vagueness), and metacognitive comments about the problem solving process (e.g., “I’m confused here”). They found that children who subsequently mastered the task were higher on all four measures of pretest variability than were other children, that the measures of pretest variability were only modestly related to each other, and that a composite measure of variability predicted learning more effectively than did age, instructional condition, or number of correct pretest answers. Long pauses and frequent metacognitive comments were the types of variability most strongly related to learning. In addition, all measures of variability decreased as children mastered the task.

The decrease in variability with increasing task mastery suggests that the positive relation between initial variability and learning is due to children whose initial behavior is highly variable being in a state in which they are especially likely to learn, rather than to the high variability being a stable characteristic of good learners. Whether there are in fact consistent individual differences in variability is unknown. A number of investigators have hypothesized that gifted and creative people are especially high in variability (Gardner, 1993; Janos & Robinson, 1985; Stokes, 2001), but some data argue against the hypothesis (Coyle, Read, Gaultney, & Bjorklund, 1998).

Not all types of variability are positively related to learning. Coyle (2001) examined five measures of variability on sort-recall tasks, a type of problem on which multiple strategies can be used within a given trial: number of strategies used at least once during the experiment, mean number of strategies used on each trial, number of pairs of consecutive trials on which different strategies were used, mean number of strategies added and deleted on consecutive trials, and number of strategy combinations used on different trials. A factor analysis of the data on these measures from eight sort-recall experiments indicated two main factors: strategy diversity and strategy change. The first two measures loaded most heavily on the strategy diversity factor, the last three on the strategy change factor. Consistent with past findings, the strategy diversity factor, which corresponded to the kinds of variability described previously in this section, correlated positively with recall. In contrast, strategy changes, the factor on which the last three measures loaded most heavily, correlated negatively with recall. It seems likely that this negative relation was generated by recall failures leading children to shift strategies from one trial to the next or to try new combinations of strategies. More generally, distinguishing among types of variability and determining their relation to learning seems a crucial task for future research.

Significance for Analyzing Change. Accurately assessing within-child variability allows more precise theoretical analyses of how learning occurs than would otherwise be possible. In particular, trial-by-trial assessments allow researchers to analyze the contributions to learning of four component processes: acquisition of new approaches, increasing use of the most advanced existing approaches, increasingly efficient execution of approaches, and improved choices among approaches.

To illustrate how this taxonomy can be used to analyze learning, consider Lemaire and Siegler’s (1995) study of the growth of proficiency in single-digit multi-
plication among French second graders. The children’s strategy use, accuracy, and speed was observed three times during the year: 1 week, 3 months, and 5 months after the beginning of multiplication instruction. Multiplication skill greatly increased over this period. Contrary to what might have been expected, however, the learning did not reflect addition of new strategies: from the first assessment, which was conducted within a week of the beginning of multiplication instruction, children used the same strategies—retrieval, repeated addition, and guessing—as they did 5 months later. Instead, increased multiplication proficiency reflected the operation of the other three processes. There were large changes in the relative frequency with which the three approaches were used; use of retrieval increased, whereas use of the other two strategies decreased. The adaptiveness of choices among strategies improved; children increasingly focused their use of retrieval on the problems on which retrieval was most likely to yield the correct answer. Finally, efficiency of execution showed large improvements; children executed repeated addition and retrieval far more quickly and accurately at the end of the year than at the beginning.

The finding that improved execution of strategies was a major contributor to learning is not limited to second graders’ multiplication. Although contemporary analyses of higher-level cognition have tended to emphasize the contributions of qualitative changes, such as acquisition of new strategies and representations, microgenetic analyses have consistently indicated that quantitative improvements in execution of strategies also play a large role. For example, Schauble (1990, 1996), Kuhn et al. (1995), and Kuhn and Phelps (1982) found that even when children and adults performed ideal experiments for identifying the effects of a given variable, the adults were more likely to learn the effect of the variable, because they more accurately remembered what they did and what happened in the experiment. Chen and Siegler’s (2000) examination of toddlers’ tool use, P. H. Miller and Aloise-Young’s (1995) analysis of preschoolers’ selective attention strategies, and Shrager and Callanan’s (1991) observations of mothers and preschoolers cooking together are three other cases in which improved execution of strategies contributed substantially to learning.

Another way in which assessment of within-child variability can enhance analyses of learning is through providing sufficiently detailed data to allow investigators to focus on the most informative children and strategies. Trial-by-trial analyses often indicate that all of the learning shown by a group of children derives from a subgroup of the children; focusing analyses on this subgroup can provide a much sharper focus on how learning occurred than mixing their data with data from children who learned little or nothing (Schlagmüller & Schneider, 2002; Siegler & Svetina, 2002). For example, identifying a subgroup of children who showed substantial learning allowed Gelman, Romo, and Francis (2002) to make more precise statements about changes in ESL students’ science notebooks than would otherwise have been possible. Similarly, examining within-child variability allows identification of strategies that do and do not produce learning, which again allows more focused analyses of learning processes than would otherwise be possible. Blöte, Resing, Mazer, and Van Noort (1999), for example, found that on a selective attention task, all of the learning of the 4-year-old participants derived from improved ability to execute one of the three strategies that they used, and Siegler (1995) found that 5-year-olds’ learning of number conservation was entirely attributable to increased reliance on one of the five strategies that they used.

Significance for Identifying Change Mechanisms. Examination of within-child variability also has promoted formulation of mechanisms that specify how such variability leads to cognitive growth. Among these mechanisms are ones for bridging between less and more advanced strategies (Granott et al., 2002), for coordinating multiple types of knowledge and procedures through metacognitive understanding (Kuhn, 2002; Lee & Karmiloff-Smith, 2002), for progressively shifting strategy choices toward the more effective approaches (Siegler & Shipley, 1995), and for indicating how gesture-speech mismatch contributes to cognitive growth (Goldin-Meadow & Alibali, 2002).

Findings from microgenetic studies also convey general lessons relevant to a variety of mechanisms. One such lesson involves the existence of conceptual constraints on learning. Contrary to the emphasis of earlier learning theories on blind trial-and-error, microgenetic analyses indicate that children’s learning in meaningful domains shows remarkably little trial and error (Bidell & Fischer, 1994; Siegler & Jenkins, 1989). Thus, even untutored 1- and 2-year-olds do not choose randomly among tools when they start to use them; they prefer tools that have the right type of head for pulling in the desired object and that are long enough to reach it (Chen
& Siegler, 2000). As discussed in more detail in the section on learning mechanisms, such findings suggest the existence of mechanisms that constrain children’s strategies to ones that are conceptually plausible.

Another general lesson of findings regarding within-child variability is that seemingly insignificant variations in children’s initial behavior can exert large influences on subsequent strategy discoveries. For example, Thornton (1999) found that 5-year-olds who played the game “20 Questions” typically began by asking whether the answer was a particular object. However, the exact phrasing that they used proved surprisingly predictive of their learning beyond this point. In a game that included several cars as potential answers, only 10% of children who initially asked questions that clearly specified the object of interest (e.g., “Is it the red car?”) or who did not name any object characteristics (e.g., “Is it one of the cars?”) progressed to asking questions that were informative about multiple objects (e.g., “Is it one of the cars?”). In contrast, 90% of children who initially used a slightly different, ambiguous phrasing (e.g., “Is it the car?”) later asked these more informative questions. Thornton hypothesized that the very ambiguity of asking questions such as “Is it the car?” when multiple cars were present made it easier to advance to more informative questions such as “Is it a car?” or “Is it one of the cars?” Similarly, Childers and Tomasello (2001) found that 2.5-year-olds who were presented verbs with pronoun frames (e.g., “He kicked it”; “She pushed it”) were more likely than peers who heard the same verbs with more specific noun frames (e.g., “Sam kicked the ball”; “Jane pushed the car”) to generalize the past tense form to novel verbs (e.g., “She tunned it”; “Jane tunned the car”). The authors hypothesized that the greater consistency of the pronoun frames facilitated learning and generalization of the past tense verbs by making it easier for the children to focus on the verb ending. Thus, subtle differences in the conditions of learning can lead to substantial variation in the learning that occurs.

Influences of Child and Environment

Within-Child Variability

Amount of within-child variability often changes over the course of development, but the changes do not conform to any single pattern. With age and experience, variability can increase (Coyle & Bjorklund, 1997; Dowker, 2003), decrease (Braswell & Rosengren, 2000; Spencer et al., 2000), increase and then decrease (Gershkoff-Stowe & Smith, 1997; Verijken & Thelen, 1997), stay constant (Flynn et al., 2004; Siegler, 1987), and so on.

Microgenetic studies of children’s learning suggest that these disparate patterns may have a common source. Over the course of development, performance often oscillates between less and more variable periods. Therefore, the changes with age and expertise that are observed in any particular study depend on the part of the cycle that is observed. The basic idea that periods of stability (i.e., low variability) alternate with periods of transition (i.e., high variability) was proposed by Piaget (e.g., 1975), and similar ideas have since been suggested by Siegler and Taraban (1986), Goldin-Meadow, Alibali, and Church (1993), Thelen (1994), and van Geert (1997), among others. Microgenetic studies provide considerable support for the idea.

One source of support for the view that variability tends to wax and wane in a cyclical fashion comes from studies of Piagetian problem-solving tasks. On such problems, children often begin with a systematically wrong approach, then move to a variable state in which they oscillate among a variety of strategies, and then move to relatively consistent use of a more advanced approach. This pattern has emerged among children learning about balance scales (Siegler & Chen, 1998), matrix completion (Siegler & Svetina, 2002), and conservation (van der Maas & Molenaar, 1996). The pattern has emerged in microgenetic studies of other reasoning problems as well. For example, Hosenfeld et al. (1997) found that on an analogical reasoning task, children who began the study with a consistently incorrect approach moved over eight sessions toward almost equal use of three different approaches. In contrast, children who began in a more variable state, in which they fairly often used all three approaches, moved toward consistent use of the single most advantageous approach.

Another source of support for the conclusion that variability is cyclical comes from studies of motor development. Many infants, after an early period of bias toward reaching with the right hand, oscillate among varied reaching approaches (e.g., sometimes reaching with both hands, sometimes reaching with one hand, and sometimes reaching with the other) for a prolonged period before eventually returning to consistent right-handed reaching (Corbetta & Thelen, 1999). Similarly, infants’ spontaneous kicking oscillates between periods of stability, in which a single form dominates (e.g., kicking one leg only), and periods of instability, in which several forms are used (e.g., kicking one leg re-
between-right and left leg kicks) (Thelen & Corbetta, 2002).

The oscillation between periods of lesser and greater variability is also evident in within-trial analyses. When given relevant experience on mathematical equality problems, children who initially produced the same type of incorrect strategy in speech and gesture tended to progress to a more variable state, in which their gestures reflected a correct strategy and their speech did not. In contrast, children who were given the same relevant experience but who began in a variable state, in which their gestures but not their speech expressed a correct strategy, usually progressed to a less variable state, in which gesture and speech expressed the same correct strategy (Alibali & Goldin-Meadow, 1993).

Performance of children in the same experiment who did not receive relevant experience provides a different type of support for the cyclical interpretation. Children who were initially in a variable state, in which their gesture expressed a correct strategy and their speech did not, often regressed to a consistent state, in which both were incorrect. In contrast, as noted in the previous paragraph, children who were initially in the variable state were especially likely to progress to a more advanced stable state if they did receive relevant experience. This finding suggests that high gesture-speech variability may signal “teachable moments” that need to be seized or otherwise be lost. To summarize, findings from microgenetic studies suggest that the disparate observations of age trends in variability are due to the observations tapping different phases of cyclical increases and decreases in variability.

One question raised by this perspective is whether there is a typical pattern of change in within-child variability with increasing age and knowledge. Siegler and Taraban (1986) addressed this question by suggesting the moderate experience hypothesis: that children usually progress from low variability when they have little relevant experience with the task to high variability when they have a moderate amount of experience, to low variability when they have substantial experience with it. The logic is that children often begin with only one or a few ways of solving a problem, then generate a larger variety of ways, and then settle on the best way or ways. Certainly, many examples fit this model: arithmetic, matrix completion, false belief, mathematical equality, and number conservation, to cite five (Alibali & Goldin-Meadow, 1993; Church & Goldin-Meadow, 1986; Flynn et al., 2004; Geary, 1994; Siegler & Svetina, 2002). Determining whether it is the most common progression, however, is complex. Some questions are definitional: are we talking about variability on a single, narrowly defined type of problem or variability across a whole domain of problems? To illustrate with an everyday example, professional basketball players possess a far greater range of shooting motions than do high school players, but for any single type of shot (e.g., free throws), their motions are far less variable (Gilovich, Vallone, & Tversky, 1985). A second issue is whether we are talking about adaptive or nonadaptive variability. Returning to the basketball example, non-adaptive variability (e.g., variation in the motion of free throws) may decrease with experience, but adaptive variability (e.g., the variety of effective adjustments that can be made when a taller defender unexpectedly comes to block a lay up) may increase. A third issue is whether we are talking about competence or performance. A professional basketball player may know more ways of shooting free throws than a high school player, but may be less variable in her performance in games.

Resolving this question is well beyond the limits of this paper, but it certainly is an important and interesting challenge for future research.

**Between-Child Variability and Learning**

Learning is influenced by between-child as well as within-child variation. Not surprisingly, age is a particularly pervasive influence. Older toddlers learn to use tools more rapidly and consistently than do younger toddlers (Chen & Siegler, 2000). Older preschoolers learn how to bake a cake from watching and interacting with their mothers more effectively than do younger preschoolers (Shrager & Callanan, 1991). Older elementary school students learn more rapidly from experience with Tower of Hanoi problems than do younger students (Bidell & Fischer, 1994). Adults learn more rapidly than 10-year-olds about the effects of variables on unfamiliar scientific reasoning problems and about how to perform controlled experiments (Kuhn et al., 1995; Schauble, 1996).

Between-child variation in initial knowledge also exercises a pervasive influence on learning. Children who use defined rules, as opposed to guessing or not using any systematic rule, show greater learning regarding balance scales (Siegler & Chen, 1998), biological concepts (Opfer & Siegler, 2004), gear problems (Dixon & Bangert, 2002), and scientific experimentation (Kuhn & Phelps, 1982). Similarly, children who can verbalize rules as well as generate responses consistent with them
show greater learning than peers who cannot verbalize
the rules but generate similar nonverbal responses (Pine & Messer, 2000). Among children who use systematic
rules, those who use more advanced pretest rules learn
more about balance scales (Chletos & De Lisi, 1991).
Children with more advanced conceptual knowledge of
a domain are superior in learning procedures for solving
problems in the domain (Rittle-Johnson & Alibali, 1999; Rittle-Johnson, Siegler, & Alibali, 2001). Knowledge
of which features of problems to encode is also
positively related to subsequent learning, as indicated
by findings on balance scale and mathematical equality

Numerous sources of between-child variability other
than age and initial knowledge also influence learning.
Children with higher IQs tend to learn more than peers
with lower IQs (K. E. Johnson & Mervis, 1994; Siegler & Svetina, 2002). Children who place a greater value on
organization are more likely to learn organizational
memory strategies than are ones who do not place as
great a value on organization (Schlagmüller & Schnei-
der, 2002). Quality of social relationships also influences
learning; children learn more about writing when they
 colaborate with friends than with other classmates
(Jones, 1998; Jones & Pellegrini, 1996).

Theoretical Implications and Questions

One implication of research on within-child variability
is that typical cross sectional and long-term longitudi-
nal studies systematically exaggerate the changes that
occur with age. Sampling at wide intervals makes
change appear more abrupt than when sampling is more
frequent, because it often eliminates periods of high
variability and short-term regressions. In a clever recent
demonstration of this point, Robinson, Adolph, and
Young (2004) simulated varying sampling intervals by
systematically removing observations from a high-den-
sity (daily) sampling of infant motor activities. They
found that the wider the sampling interval, the more
stage-like that development appeared.

A related problem is that classifying children as pos-
sessing an ability when they reach some arbitrary crite-
rion (e.g., 75% correct) leads to ignoring the partial
understanding manifested earlier. Children who use an
advanced strategy on 25% of trials, for example, often
are classified as if they had no understanding, when in
fact they clearly do have some understanding. Conser-
vely, failures to apply the desired reasoning at the
older age are ignored as long as the child meets the cri-
terion, again leading to the amount and abruptness of
change appearing to be greater than they are. Such exag-
gerrated depictions of change may have contributed to
the field’s traditional weakness in explaining change, by
seeming to demand mechanisms that produce larger and
more rapid changes than the changes that actually occur.

Another intriguing theoretical issue concerns why
within-child variability tends to be positively related to
subsequent learning. Several explanations have been ad-
vanced. Dynamic systems theory postulates that for a
system to change, it must first become unstable (Hosen-
feld et al., 1997; Thelen & Corbetta, 2002). Variability
in the behavior of interest is one sign of such instability.
Another hypothesis is that variability reflects simulta-
neous activation of conflicting representations, which
facilitates the extension of the more advanced representa-
tion from one modality to the other (Goldin-Meadow
& Alibali, 2002). A third interpretation is that new
strategies are often constructed from subroutines of ex-
isting approaches, and that assembling subroutines from
different strategies is easier if the relevant strategies
have been used recently and thus are relatively active
(Siegler, 2002).

Although different in their particulars, all of these
interpretations have a common core: Learning is most
likely when previously dominant approaches weaken.
This weakening can come about in varied ways: through
the dominant approach failing, as when it results in neg-
ative feedback; through the learner being asked to ex-
plain why dominant incorrect approaches are incorrect;
or through changes in other aspects of the system, as
when improved postural control changes infants reach-
ing. The general lesson is that change reflects not only
the emergence and strengthening of new variants, but
also the weakening of previous approaches.

With regard to differences between children, one
issue that has only begun to be addressed concerns the
determinants of individual differences in variability.
One factor that appears to be important is the conditions
under which children first acquire knowledge in the do-
main. Stokes (1995) demonstrated that if initial learning
occurs under conditions that require highly variable re-
spending, the high variability persists, even when the
conditions change and high variability is no longer re-
quired or advantageous. In contrast, introducing the re-
quirement of high variability later in learning does not
produce a similar effect; participants produce high vari-
ability while it is rewarded, but return to lower levels of

variability once the requirement is no longer in effect. Personality and cognitive style differences also may contribute to such individual differences (Stokes, 2001).

Path of Change

One of the appealing aspects of the new field of children’s learning is that it integrates quantitative and qualitative aspects of change. This is perhaps best exemplified by the new field’s depiction of the path of change.

Basic Phenomena

In many tasks and domains, children (and adults) display qualitatively discrete understandings, such as rules, strategies, theories, mental models, and schema. Piagetian, theory-theory, and many information-processing approaches suggest that children progress through a regular developmental sequence of such understandings. Young children show a single, simple understanding; older children a different, more advanced understanding. Youn g children show a single, simple understanding; older children a yet more advanced understanding; and so on.

The pervasive within-child variability described in the previous section indicates that such depictions of developmental sequences are too simple. Children cannot progress from one approach to another if at all times they know and use multiple understandings. However, this does not mean that the basic idea of the developmental sequence needs to be abandoned. Instead, the implication is that accurate depictions of the path of change must incorporate not only acquisition of new, qualitatively distinct approaches, but also quantitative changes in the frequency of use of both new and previous approaches.

Even infants progress through regular, age-related sequences of multiple, qualitatively distinct approaches. As noted earlier, infants use a variety of approaches to descend down relatively steep ramps: crawling; walking; sliding head first, sliding feet first, or in a sitting position; or refusing to go down in any way (Adolph, 1997). These approaches emerge in a quite consistent order. Refusing to go down at all is the first response, other than crawling, during the period in which crawling is infants’ dominant mode of locomotion. Sliding down head first is typically the next strategy to emerge, followed by sliding down in a sitting position for some infants and sliding down feet first for others. On average, the infants used between three and four distinct descent strategies per session, with the relative frequency of these approaches changing greatly with age and experience. For example, in infants’ first weeks of crawling, they refused to go down the ramp altogether on 100% of trials on which they did not attempt to crawl down. By the time that crawling was about to give way to walking as the main locomotor strategy, infants refused to go down on only 1% of trials on which they did not attempt to crawl down.

The path of change of the 1- and 2-year-olds in Chen and Siegler (2000) showed a similar mix of qualitative and quantitative changes. When the tool use task was introduced, two approaches predominated and were equally frequent: reaching for the goal object and just sitting and looking at it. Next, reaching became the dominant approach, being used on about 65% of trials, though looking, using a tool, and asking for help also continued to be used. With experience on the task and exposure to modeling or a verbal hint, tool use increased in frequency to the point where it was employed on the majority of trials. However, all three other approaches remained as well.

Preschoolers generate similar paths of change in single-digit addition, false belief, selective attention, and other tasks (Amsterlaw & Wellman, 2004; Flynn et al., 2004; P. H. Miller & Aloise-Young, 1995; Siegler & Jenkins, 1989). For example, Siegler and Jenkins (1989) presented 4- and 5-year-olds who knew how to add but did not know the min strategy (counting from the larger addend) with 20 to 30 sessions of addition problems. At the outset of the study, the preschoolers counted from one on about 40% of trials, retrieved the answer from memory on about 25%, and used a variety of other approaches (but not the min strategy) on the remaining 35%. By the end of the study, most children had discovered two new strategies (one of which was the min approach), as well as changing their frequency of previous approaches so that retrieval became the single most common strategy. Similarly, the large majority of 3-year-olds studied by Amsterlaw and Wellman (2004) progressed over 12 sessions from never correctly answering false belief problems, to sometimes generating correct false belief reasoning, to consistently answering correctly. None of the 3-year-olds progressed directly from incorrect to consistently correct responding; instead, children required a median of three sessions from the time they first showed correct false belief reasoning to the time when they first generated consistently correct answers. In addition, all children regressed to chance level performance in at least one session after
having responded consistently correctly in a session. Thus, the path of change included a qualitative shift (the first use of correct false belief reasoning) and also a quantitative change (the gradual increase in use of such reasoning).

The broad outlines of the paths of change revealed by microgenetic studies generally have paralleled those observed in cross-sectional and long-term longitudinal studies (Kuhn, 1995; P. H. Miller & Coyle, 1999; Siegler, 2000). Microgenetic studies, however, yield fine-grain as well as broad depictions of paths of change, and thus add invaluable information about them. Some of these types of information about paths of change have already been described: the longer solution times and heightened verbal and nonverbal variability that often immediately precede discovery, for example. However, understanding of paths of change has also been enhanced by numerous other findings from microgenetic studies.

One such contribution is information about short-lived transitional approaches. Certain phenomena that are seen only briefly, and sometimes not very often even then, are nonetheless crucial to understanding the learning process. One example involves naming errors during vocabulary acquisition. When toddlers start to speak, they name objects with inconsistent accuracy. Sometimes they give the correct word to name objects, but they frequently did so during the transition period. This transition period was brief and emerged at different ages for different children, probably because it was more a function of vocabulary size than of age; thus, the phenomenon would have been unlikely to be discovered without dense sampling of changing competence.

Numerous other paths of change also have been illuminated by detailed observation of transition periods. One example emerged in Karmiloff-Smith’s (1979b) microgenetic study of map drawing. She found that after generating maps that were entirely sufficient for purposes of the task, 6- to 11-year-olds sometimes began to generate redundant markings that were unnecessary for purposes of solving the problem but that reflected the children’s increasing metaprocedural understanding of their own strategies. Chiu, Kessel, Moschkovich, and Munoz-Nunez’s (2001) examination of a seventh graders’ learning how to graph linear functions provides another example. In response to instruction, the child neither adopted the instructed strategy nor persisted with his original approach. Instead, he merged the two in an unanticipated way, using the instruction to create a refined version of his original approach.

In addition to revealing unsuspected transitional strategies, microgenetic analyses also sometimes reveal that hypothesized transition states do not occur or are not part of the transition. In Siegler’s (1995) study of number conservation, no child was observed vacillating between reliance on the length of a row and reliance on its density, the transitional strategy hypothesized by Piaget (1952). In a study of single-digit addition, Siegler and Jenkins (1989) found that a transition state between the sum and min strategies that had been hypothesized by Neches (1987)—counting-on from the first addend—was not used by any child. In a study of categorizations of life status, Opfer and Siegler (2004) observed all three states that had been hypothesized previously (Hatano et al., 1993): the E-Rule (everything is alive), the A-Rule (only animals are alive), and the L-Rule (only plants and animals are alive). However, none of the children followed the hypothesized progression from the E-Rule to the A-Rule to the L-Rule. Instead, all children who used the E-Rule on the pretest progressed directly to the L-Rule.

The trial-by-trial analyses of microgenetic studies yield sufficient data about individual children’s learning to examine the consistency of the path of change across individuals. Often, the path has proven to be quite consistent. For example, in Siegler and Stern’s (1998) study of discovery of an arithmetic insight strategy, 13 of the 16 children in one group progressed through the same sequence of four strategies (in terms of the order in which they first used each strategy), and 2 of the other 3 children used the same four strategies but reversed the order of the first two approaches.

Deviations from the usual path can also be informative. On mathematical equality problems, for example, some children progress directly from a state in which both gesture and speech express the same incorrect understanding to a state in which both gesture and speech
express the same correct understanding, thus skipping
the usual intermediate state of gesture-speech mismatch
(Perry, Church, & Goldin-Meadow, 1988). Deviating
from the typical path in this way is associated with nar-
rower generalization than following it. Most children
who follow the usual sequence generalize their under-
standing of the equal sign, which they learned in the con-
text of addition, to multiplication, whereas most children
who deviate from the usual sequence do not generalize to
multiplication (Alibali & Goldin-Meadow, 1993).

By allowing identification of the trial of discovery
(the trial on which a child first used a new strategy), mi-
crogenetic methods have also made it possible to exam-
ine the experience of discovery. Such examinations
indicate that even for a single task, experimental proce-
dure, and discovery, the experience varies a great deal
among individuals. Of the 4- and 5-year-olds in Siegler
and Jenkins’ (1989) study of discovery of the min strat-
y, for example, some children were highly aware of
using a novel strategy and commented on it, whereas
others showed no awareness of having done anything un-
usual. Even among those who were aware of using a new
approach, some were excited and others not. The exper-
iential aspects of discovery seem to have longer-term
consequences; those children who were aware of using a
new strategy subsequently generalized it more exten-
sively than those who did not. Excitement at making a
discovery seems to have similarly positive effects on
adults’ generalization of new approaches (Siegler &
Engle, 1994).

Influences of Child and Environment

As noted earlier, the path of change tends to be similar
among different children of the same age exposed to the
same experimental procedure. The commonality in
paths of change extends further as well. Children who
show similar initial knowledge of a task but who are of
different ages tend to progress along the same path. On
tool use problems, both 1- and 2-year-olds first either
just looked at the goal toy or reached for it; then, reach-
ing became the main strategy with the tool strategy also
becoming fairly frequent; then, use of tools became
dominant, with increasing focus on the optimal tool
(Chen & Siegler, 2000). Similarly, 4- and 5-year-olds
progressed through the same set of balance scale rules
when both were presented feedback on their answers
and asked to explain the reasoning that led to the exper-
imenter’s answers (Siegler & Chen, 1998).

Even when both age and initial knowledge differ, the
path tends to be similar. For example, Kuhn et al. (1995)
found that although adults’ scientific reasoning started
at a more advanced level than that of 10-year-olds, the
children and adults progressed along a common path of
theory-evidence coordination. The path involved first
noting that evidence from experiments is relevant to be-
liefs about the causal status of variables; then suppor-
ting prior beliefs that a variable matters by citing a result
from a single experiment that is consistent with the prior
belief; and then supporting prior beliefs that a variable
does not matter by citing single instances consistent
with that belief. Next comes citation of multiple obser-
vations to justify prior beliefs, followed by the develop-
ment of controlled experimentation and a gradual
increase in the frequency of valid inferences on the basis
of the experimental evidence. Adults tended to start fur-
ther along this path and to progress further along it than
the 10-year-olds, but the progression was the same.

The path of change also tends to be similar for chil-
dren with and without mental retardation. For a task on
which external memory aids could be used to help re-
member the location of objects, children with and with-
out mental retardation who were matched for mental age
showed the same path of change. Both groups initially
did not use the external memory aids, then manipulated
individual tokens but did not place them in ways that
would help in recalling the target locations, and then
arranged the objects so that they provided straightfor-
ward cues to the locations that needed to be remembered
(Fletcher & Bray, 1995). Similarly, Fletcher et al.
(1998) reported that 8-year-olds with mild mental retar-
dation showed a path of change in basic arithmetic simi-
lar to that of the typical preschoolers in Siegler and

This consistency of the path of change across individu-
als is not perfect. In most studies, people vary some-
what in their paths of change. This is true even in the
studies cited above as illustrations of the consistency of
change across individuals. For example, in Siegler and
Jenkins (1989), discovery of the shortcut sum strategy
usually was followed quickly by discovery of the min
strategy, but one child in the study discovered the min
strategy without ever using the shortcut sum, and an-
other child used the shortcut sum many times over a pro-
tracted period before discovering the min approach.
Sometimes there are two common paths of change.
In one such case, Lavelli and Fogel (2002) examined
amount of infant-mother communication on a weekly basis over the infants’ first 14 weeks. They found that for roughly half of infant-mother dyads, face-to-face communication increased steadily over the period, whereas for the other half, the amount of communication increased until about 8 weeks and then steadily decreased. Another example of inter-child variability in the path of change comes from the area of motor development. Spencer et al. (2000) observed babies’ reaching each week between 3 and 30 weeks and every other week between 30 and 52 weeks. The components involved in development of stable reaching were similar across infants—improved control of the head and upper torso, independent sitting, ability to extend the hand to a distant target, and ability to touch and grasp nearby objects—but different infants mastered the components in different orders.

Theoretical Questions and Implications

These results indicate that the traditional view of developmental sequences is outdated; children rarely progress directly from one consistent understanding to a different consistent understanding to a third consistent understanding. Both the amount of within-child variability—children using multiple approaches over protracted time periods—and the amount of between-child variability—different children showing different paths of change—indicate that the traditional conception is too simple.

The findings raise the issue of whether it makes sense to talk at all about developmental sequences in a post-Piagetian world. I think that it does, because it calls attention to a central developmental phenomenon: that children generate increasingly adequate, qualitatively distinct, strategies and understandings prior to mastering concepts and problem solving skills. These partially correct strategies and understandings frequently reflect broadly applicable ways of thinking that children apply when they lack superior alternatives, for example 5-year-olds focusing exclusively on the single most salient dimension on liquid quantity conservation, balance scale, shadow projection, and other problems.

The challenge, then, is to refine the concept of developmental sequences so that it is consistent with current data on paths of change yet also as parsimonious as possible given those data. One promising approach would be to recognize that developmental sequences are multifaceted and therefore need to be characterized in multiple ways. For example, the path of change might be characterized in terms of the order in which strategies are first used, also in terms of the order in which different strategies become the single most common approach, and also in terms of the mixture of strategies used at various points. In some cases, the first and second of these characterizations will coincide, as they did in Siegler and Stern (1998). In other cases, each approach will yield a unique perspective, as when some early developing strategies never become common (as in Siegler & Jenkins, 1989). Together, these multiple depictions of paths of change may contribute to an accurate and nuanced understanding of developmental sequences.

Rate of Change

Both scientific and everyday theories about strategy discovery vary greatly in the rate of change they envision. Theories that emphasize trial and error suggest that discovery of new approaches will be a slow process; theories that depict discoveries as arising from flashes of insight, as in the tale of Archimedes in the bathtub, suggest a rapid if not instantaneous rate of change.

The concept rate of change can be usefully divided into two components: amount of time/experience before the first use of a new approach (here labeled the rate of discovery, and amount of time/experience before frequency of the new approach reaches its asymptotic level here labeled the rate of uptake). Distinguishing between the two types of information is essential, because the relation between them varies considerably. Sometimes, discovery is quite rapid but uptake takes a long time. For example, second graders in Siegler and Stern (1998) took an average of only seven trials to discover an arithmetic insight strategy, but did not use the strategy on the majority of trials in any session until five sessions (100 trials) later. In contrast, kindergartners in Siegler and Svetina (2002) required an average of about 50 trials before they discovered a correct strategy for solving matrix completion problems, but required only about 12 trials beyond that point to use it consistently.

Experimental conditions also affect the two rates of change differently. For example, in Opfer and Siegler’s (2004) study of categorization of life status, the teleology condition led to slower discoveries than did the two other experimental conditions, but once the discovery was made, its uptake was much faster in the teleology condition. In Blöte et al. (2004), discoveries occurred most often on easy problems, but uptake of the new strategy was comparable on easy and difficult problems.
In Siegler and Jenkins (1989), introducing challenge problems did not influence the rate of discovering the min strategy, but it greatly increased the uptake of the strategy among children who already had discovered it. Thus, a comprehensive description of the rate of change requires information regarding both the rate of discovery and the rate of uptake.

**Basic Phenomena**

Perhaps the most basic question regarding the rate of discovery is whether discoveries tend to be made quickly or slowly. Phrased in terms of models of discovery, a good answer might be “Faster than connectionist models imply, slower than symbolic models imply.” Connectionist models tend to discover new approaches extremely slowly (to the extent they discover them at all). For example, McClelland’s (1995) model of balance scale learning requires thousands of trials to learn each new rule. Clearly, children discover new rules much faster than that. On the other hand, children rarely discover new rules in a single trial, as symbolic approaches such as Newell’s (1990) model of balance scale learning do. Instead, results from microgenetic studies suggest that when feedback is given (as presupposed in both connectionist and symbolic models), discoveries usually take anywhere from a handful of trials to a few hundred trials. We might label this human-scale learning.

The difference between human scale learning and that of connectionist and symbolic models is evident in the difference between Siegler and Chen’s (1998) empirical data on 5-year-olds’ discovery of balance scale rules and the discovery of the same rules by McClelland’s (1995) and Newell’s (1990) simulation models. Over the course of 16 problems, two-thirds of the 5-year-olds in Siegler and Chen (1998) who initially used Rule I discovered Rule II. Sixteen trials is reasonably representative of human scale discovery, but it is far different from either a single trial or thousands of trials. Rates of strategy discovery vary considerably across studies, depending on characteristics of the children, experimental situation, and relation between old and new strategies. However, as the Siegler and Chen results indicate, discovery is rarely as fast as symbolic models suggest or as slow as connectionist models imply.

Children’s learning tends to differ from that of the simulation models not only in the rate of discovery but also in the rate of uptake. Both symbolic and connectionist models tend to use a superior new strategy consistently on a given problem once the strategy has been discovered and used on that problem. Children, however, often extend newly discovered strategies surprisingly slowly. The relatively slow extension of advanced thinking extends even to problems that are viewed as reflecting fundamental developmental advances that have broad ramifications for a wide range of thought. For example, 43% of children who were just beginning to use transformational reasoning on number conservation problems used that reasoning again when the same problem was presented two sessions (24 trials) later, and 76% used it when the same problem was presented four sessions (48 trials) later (Siegler, 1995). The same relatively slow uptake is usually evident when new problems are structurally identical but differ in their particulars from earlier ones. Thus, in three microgenetic studies of acquisition of understanding of false belief (Amsterlaw & Wellman, 2004; Flynn, 2005; Flynn et al., 2004), uptake was quite gradual. Only 4 of 13 3-year-olds who acquired understanding of false belief in Flynn et al. (2004) consistently displayed such understanding thereafter. Similarly, all children in Amsterlaw and Wellman (2004) who improved their false belief understanding regressed from one session to the next at least once during the study, though the overall trend was toward improved performance.

Slow uptake of new ways of thinking has been documented with a wide variety of other tasks and age groups as well. For example, 4-year-olds who spontaneously used rather sophisticated analogical reasoning strategies in one session often regressed to less sophisticated strategies for several sessions thereafter (Tunteler & Resing, 2002). Regressions have also been found to be common in the quality of 4-year-olds’ storytelling (McKeough & Sanderson, 1996), in 8-year-olds’ use of organizational memory strategies (Coyle & Bjorklund, 1997), in 11-year-olds’ solving of gear problems (Perry & Lewis, 1999), and in adults’ use of scientific reasoning strategies (Kuhn et al., 1995).

Uptake of new strategies tends to be slow even when children can explain why the new approach is superior to the old. For example, in Siegler and Jenkins (1989), one child, on her trial of discovery of the min strategy, explained why she didn’t count from one by saying, “Cause then you have to count all those numbers” (p. 66). Another child in the same study commented on her first use of the min strategy by saying, “Yeah—smart answer”
yet, both of these children, like others in the study, generalized use of the new strategy quite slowly (though faster than children whose visible behavior indicated that they had used the min strategy but who claimed that they had counted from one). Although uptake of newly discovered strategies is generally quite slow, this is not always the case. For example, Schlagmüller and Schneider (2002) found that 8- to 12-year-olds adopted an organizational strategy for remembering groups of objects quite rapidly once they began to use it, and Thornton (1999) observed similarly rapid uptake of an efficient strategy for playing “20 Questions” in a 5-year-old. A number of factors that have been found to influence the rate of discovery and uptake of new strategies are considered in the next section.

Influences of Child and Environment

Rates of both discovery and uptake increase with age. Toddlers between 27- and 35-months discover effective tool use strategies more rapidly than 18- to 26-month-olds and their uptake of the strategy is also quicker (Chen & Siegler, 2000). Among preschoolers, 5-year-olds are faster than 4-year-olds to learn that certain relations are indeterminate (Klahr & Chen, 2003). The trend continues with older children; 13-year-olds are quicker than 10-year-olds to discover and generalize an organizational strategy to enhance memory (Bjorklund, 1988), and adults are more likely than 10-year-olds to discover and generalize effective scientific experimentation and inference strategies (Kuhn et al., 1995; Schaubé, 1996). To illustrate the magnitude of the differences among age groups that sometimes emerges, in Thornton (1999)’s study of how children build toy bridges, 5-year-olds required more than three times as many trials as 7-year-olds to discover an insightful strategy. In addition, younger children sometimes fail to maintain learning under circumstances in which older peers do so. For example, 4-year-olds who received training in understanding indeterminate relations frequently regressed when their understanding was assessed 7 months later, though all 5-year-olds maintained their original learning (Klahr & Chen, 2003).

Other characteristics with which children enter studies also influence their rate of learning. Rates of discovery and uptake of new approaches tend to be greater for children with higher IQs (K. E. Johnson & Mervis, 1994; Siegler & Svetina, 2002). Similarly, children who start with more advanced rules tend to progress to yet more advanced approaches more rapidly than children whose initial rules are less advanced (Fujimura, 2001; Siegler & Chen, 1998). Relatively advanced encoding and conceptual understanding are also associated with rapid discovery and uptake of new approaches (Rittle-Johnson et al., 2001; Siegler & Chen, 1998).

In addition to these influence of child variables, a variety of experiential variables also influence rates of discovery and uptake. Direct instruction in problem solving produces faster discovery and uptake of new approaches, through narrower generalization, than does instruction in underlying principles (Alibali, 1999; Opfer & Siegler, 2004). Exposure to a model who both selects the most appropriate tool and demonstrates how to use it to obtain the goal leads to faster discovery and uptake of the new approach than does a verbal hint that identifies which tool to use but does not demonstrate its use (Chen & Siegler, 2000). Encountering problems that are moderately beyond current understanding produces faster discovery than encountering ones that are far beyond it (Siegler & Chen, 1998).

Relations between new and existing approaches also exert a large influence on the rate of uptake of new approaches. Strategies that offer large advantages in accuracy and speed on the problems being presented have a faster rate of uptake than strategies that offer smaller advantages. Evidence for this point can be found in Siegler and Jenkins’ (1989) 11-week study of discovery of the min strategy. The first 7 weeks of this period were spent on problems with addends 1 to 5. Exposure to such problems led most children to discover the min strategy, but only to very gradual uptake of it. Therefore, in Week 8, Siegler and Jenkins presented children with challenge problems, problems such as 22 + 3, on which counting from 1 would work badly but on which the min strategy would work well. Encountering the challenge problems led children who had already discovered the min strategy to greatly increase their use of it, not only on those problems but on subsequent small addend problems as well.

Between-experiment evidence is consistent with this conclusion that uptake (but not necessarily discovery) is faster when the new strategy has large advantages over previously discovered alternatives for solving the types of problems being presented. Problems on which the new strategy leads to consistently correct performance, and on which older strategies lead to systematically incorrect or chance performance, evoke the fastest uptake of new strategies. Thus, uptake of new strategies has been relatively rapid on mathematical equality, number conservation, matrix completion, Tower of Hanoi, and balance scale tasks (Alibali & Goldin-Meadow, 1993;
Bidell & Fischer, 1994; Church & Goldin-Meadow, 1986; Siegler & Chen, 1998; Siegler & Svetina, 2002). Uptake is slower when the new strategy produces smaller improvement in accuracy and when its main advantage is speed. Examples include use of the arithmetic shortcut strategy rather than addition and subtraction to solve $A + B - B$ problems (Siegler & Stern, 1998), use of systematic experimental design strategies rather than unsystematic comparisons to learn about the causal influence of variables (Kuhn & Phelps, 1982; Kuhn et al., 1995; Schauble, 1996), use of organizational strategies for remembering objects that can be organized into a few categories (Coyle & Bjorklund, 1997; Fletcher et al., 1998), and use of bridging, a strategy of envisioning a rough outline of a strategy prior to formulation of the strategy, in construction of robots and bridges (Granott, 1998; Parziale, 2002).

Even strategies that bring large benefits sometimes have relatively slow uptakes. One reason is that newly discovered strategies are subject to forgetting (i.e., to their strength diminishing below the point at which they would be chosen) and therefore sometimes need to be rediscovered. One type of evidence for the role of forgetting is that extension of new strategies tends to be more gradual in multisession microgenetic studies than in single session ones. Children fairly often continue to use a newly discovered strategy quite consistently in the session in which it is discovered (e.g., Alibali, 1999; Siegler & Chen, 1998). However, when children return a few days or a week later, they often have forgotten the strategy, thus necessitating rediscovery. This phenomenon was particularly dramatic in Siegler and Stern’s (1998) study of discovery of the shortcut strategy for solving problems of the form $A + B - B = \ldots$. After discovering the shortcut strategy, children used it on between 70% and 90% of the remaining trials in the session. However, 0 of the 15 children who discovered the shortcut approach used it on the first trial of the next session, a week later; not until the sixth trial of the new session did a majority of children again use it. By the end of that session, all 15 children were again using the shortcut strategy. However, the “off again, on again” pattern continued; even five sessions after the initial discovery, most children began the session by using the standard computation strategy (adding A and B and then subtracting C), though the rediscoveries of the shortcut strategy were made increasingly quickly in later sessions.

Forgetting plagues not only everyday discoveries but also profound ones. Wegener (1915/1966), the father of plate tectonic theory, claimed that he generated the basic idea in 1910 or 1911, shortly before his classic 1915 publication describing it. A friend, however, recalled Wegener describing the idea to him in 1903 when they were both graduate students (Giere, 1988). Thus, the cycle of discovering, forgetting, and rediscovering characterize even the most profound insights.

**Theoretical Implications and Questions**

Probably the most intriguing question raised by findings regarding the rate of change is why the uptake of effective new strategies is so often slow. After discovering a strategy that is both more accurate and logically superior to prior approaches, why not use it all the time? Several contributing factors have already been cited: forgetting of newly discovered approaches; the omnipresence and generally adaptive value of within-child variability; and associations between frequently used strategies and the types of problems on which they have been used, which must be weakened for the new approach to be chosen consistently. However, other factors almost certainly contribute as well.

One likely contributing factor is the benefits and costs of using newly discovered strategies. When children first use a strategy, they often execute it less effectively, and at a greater cost in mental resources, than will be the case after greater use (Guttentag, 1984). Such utilization deficiencies have frequently been observed in microgenetic research; indeed, because microgenetic studies allow examination of newly discovered strategies, they provide the ideal situation for observing utilization deficiencies. In one example of a utilization deficiency arising within a microgenetic study, 3- and 4-year-olds’ discovery of a potentially effective selective attention strategy did not initially improve their accuracy (P. H. Miller & Aloise-Young, 1995). In another example, 4- and 5-year-olds’ initial use of the min strategy did not improve their accuracy or solution times relative to counting from one on small number problems (Siegler & Jenkins, 1989). In a third example, 9-year-olds’ initial use of an organizational strategy did not improve their memory of the objects that had been organized (Bjorklund et al., 1992). And in a fourth particularly striking case, the first two uses of an organizational strategy led to below chance accuracy, whereas the last few uses of the same strategy produced almost perfect accuracy (Blöte et al., 1999). Thus, part of the reason for the slow uptake of seemingly useful new strategies is that the strategies at first are less useful than they later will be.
A second question regarding the rate of change (and also its path and variability) concerns the sources of within-condition variability that cannot be traced to children’s demographic characteristics or initial knowledge. Even when age and knowledge are comparable, children within any given experimental condition vary greatly in the rate of discovery and uptake of new strategies. Consider the extent of such variation in Siegler and Jenkins (1989). Among the seven children who discovered the min strategy, the first discovery occurred in the 2nd session, the last in the 22nd. Despite this substantial variation, neither age nor prior knowledge of addition nor other relevant types of numerical knowledge predicted the rate of discovery.

Similar within-condition variations due to unknown causes in rate of discovery and uptake of new approaches have arisen among other age groups and on other tasks. For example, 33% of 3- and 4-year-olds in Flynn et al. (2004) showed abrupt change over seven sessions of presentation of a seven-task theory of mind test, as defined by their at least once during the study passing posttest), whereas the other 76% did not. In P. H. Miller at least three more tasks than in the previous session. The other 67% of children showed gradual change. Similarly, 24% of the third and fourth graders in Alibali (1999) showed abrupt change (as defined by use of a nonoverlapping set of strategies on the pretest and posttest), whereas the other 76% did not. In P. H. Miller and Aloise-Young’s (1995) similar analysis of 3- and 4-year-olds’ acquisition of a selective attention strategy, the corresponding percentage of abrupt and gradual changes was 37% and 63%. Kuhn and Phelps (1982) and Siegler (1995) also found that although the majority of children showed gradual change, a minority showed abrupt change. Thus, although a variety of child and environmental variables have been found to influence the rate of discovery and generalization, much variance remains to be explained.

**Breadth of Change**

In general, learning is neither as narrow nor as broad as could be imagined. It almost always generalizes beyond the item on which a new approach was generated, and it rarely is instantly extended to all items and tasks on which the discovery is relevant. Thus, just as there seems to be a human-scale rate of learning, there also seems to be a human-scale breadth of learning.

This similarity between findings regarding the breadth and the rate of change is not coincidental. Except in cases in which the same item is presented repeatedly, the uptake of new strategies always involves problems that differ in some way from the item on which the discovery occurred. In all such instances, whether the uptake of new strategies is viewed as an issue of the rate of change or the breadth of change is to some degree a matter of definition. For purposes of this chapter, extensions of new approaches to different problems on the same task were discussed under the rate of change heading; the discussion of breadth of change in this section is limited to cases in which new approaches are extended to a different task (though even that distinction winds up being somewhat subjective, as will become evident later).

**Basic Phenomena**

Many volumes have been written lamenting children’s lack of transfer and the narrowness of their learning (e.g., Bransford, Brown, & Cocking, 1999; Cognition and Technology Group at Vanderbilt, 1997; Lave, 1988). Much less has been written about the fact that learning also tends to be far from literal. Indeed, there may be a tendency to define “transfer problems” as problems on which useful known strategies tend not to be spontaneously applied, and to define problems on which children spontaneously extend appropriate strategies as not requiring transfer.

Another reason why learning often seems narrower than our intuitions suggest it ought to be is that new strategies and capabilities can transform a familiar task into a novel one. The transition from crawling to walking provides a revealing example. As infants who could crawl but not walk gained experience with crawling, they adjusted their descent strategies increasingly precisely to their physical limits. In particular, they increasingly used descent strategies safer than crawling (e.g., sliding in a prone position) when the slope was too steep for them to crawl down safely (Adolph, 1997). When the same children began walking, however, their descent strategies became less well calibrated to their capabilities; they often tried to walk down steep slopes and fell. Thus, the new capability of walking converted a familiar task, on which children chose appropriate strategies, into a novel task that initially elicited riskier choices.

This example also illustrates another reason why learning is often narrower than seems ideal. New learners invariably face two challenges: extending their learning to the cases in which it is useful, and not extending it to the cases in which it is not useful. Accomplishing these goals requires knowing when the strategy will be useful and also often requires knowing how to
adapt the strategy to a novel context. Each of these difficulties is evident in children’s learning about mathematical equality. When third and fourth graders learn how to solve addition problems of the form \( A + B + C = + C \), many fail to transfer their learning to multiplication problems of the form \( A \times B \times C = \_ \_ \times C \) (Alibali, 1999; Alibali & Goldin-Meadow, 1993). However, learners often overextend new mathematical equality strategies to superficially similar problems on which the new strategy is not applicable. For example, after correctly solving several problems of the form \( A + B + C = + C \) by adding \( A \) and \( B \), third and fourth graders often add \( A \) and \( B \) to answer similar looking problems on which that strategy produces incorrect answers, such as \( A + B + C = \_ \_ + D \) (Siegler, 2002). In this regard, older learners are no different than 2-year-olds, who sometimes both overextend and underextend the same newly learned word (Bowerman, 1982).

Despite the difficulty posed by these twin pitfalls, learners within microgenetic studies sometimes do show impressive transfer. One context in which this has been found repeatedly is acquisition of the control of variables strategy for scientific experimentation. Second, third, and fourth graders who were provided explicit instruction in the control of variables scheme on one problem (e.g., factors influencing extension of springs) showed almost complete transfer of the scheme to superficially unrelated but structurally parallel problems (e.g., factors influencing speed of objects sinking in water). Even more impressive, the children maintained the gains over a 7-month period with no further experimental intervention (Chen & Klahr, 1999).

In this study, the transfer was to different physical reasoning tasks. Broad transfer of the control of variables scheme also has been demonstrated between physical and social reasoning. When fifth graders and adults were first presented reasoning problems in one domain (physical or social), and then presented problems from the other domain, their proportion of valid experiments and inferences in the new domain did not even temporarily diminish relative to the highest level reached in the initial domain (Kuhn et al., 1995).

An intriguing feature of this relatively broad learning of the control of variables scheme is that it can emerge as a by-product of trying to learn specific content. The children and adults in Kuhn’s and Schauble’s studies of this scheme (Kuhn, Amsel, & O’Laughlin, 1988; Kuhn & Phelps, 1982; Kuhn et al., 1992, 1995; Schauble, 1990, 1996) were not instructed in the control of variables scheme, nor did the instructions they received call attention to it. They were simply asked to find out which variables mattered on the particular tasks that they were presented. The learners made considerable progress in inferring which variables were, in fact, influential, but along the way, they also learned how to conduct experiments. Thus, relatively broad learning at times arises out of problem-solving activity aimed at meeting other goals.

### Influence of Child and Environment

Consistent with findings regarding the other components of change, the breadth of learning increases with age. Older preschoolers show broader learning than younger toddlers (Chen & Siegler, 2000), older school age children show broader learning than younger ones (Bjorklund, 1988; Dixon & Bangert, 2002), and adults show broader learning than do school age children (Schauble, 1996). When initial learning is equated, however, this relation fairly often disappears; younger preschoolers who learned an initial problem to the same extent as older ones showed comparable transfer (Brown, Kane, & Echols, 1986), as did younger elementary school and middle school children who learned balance scale and tic tac toe problems as well as older peers (Chletos & De Lisi, 1991; Crowley & Siegler, 1999).

A variety of other variables also have been found to influence the breadth of learning. Recognizing the value of new strategies influences extension of them to new problems (Paris, Newman, & McVey, 1982). Learning a strategy on problems on which the strategy is always applicable leads both to more correct extensions and to more overextensions than does learning the strategy on problems on which it sometimes applies and sometimes does not (Siegler & Stern, 1998). To the extent that the influence of variables violates learners’ expectations, they tend to perform fewer experiments about the effects of the variables and to learn less about them (Schauble, 1996).

### Theoretical Implications and Questions

One implication of these findings from microgenetic studies is that what is often taken as lack of transfer actually reflects a lack of stability in the initial learning. Particularly direct evidence for this view came from Opfer and Siegler’s (2004) study of 5-year-olds learning about biological categories. On the posttest of this study, children were asked to categorize novel plants, animals, and inanimate objects about which they earlier received feedback and also to categorize novel plants, animals, and inanimate objects.
The posttest classifications were far from perfect, but they were equally imperfect on familiar and novel items; the percent correct categorization was almost identical on the two. Given the diversity of objects within the experiment (the plants included flowers, trees, grass, beans, and clover; the animals included cats, crocodiles, bees, worms, and octopi), the breadth of learning was more impressive than would have been evident without data on use of the new categorization scheme on repetitions of the original entities. Similar evidence came from Siegler’s (1995) number conservation study, in which use of transformational reasoning on repetitions of the same problem was no higher than generalization of the reasoning to problems on which the reasoning was not used earlier. Thus, the general high variability of use of new strategies may underlie many apparent failures to transfer learning to different types of problems; distinguishing between the two interpretations requires presenting examples identical to those originally learned as well as novel examples.

A second theoretical implication concerns the crucial role of encoding of categories in determining the breadth of learning. The heterogeneity of members of each superordinate category in Opfer and Siegler (2004) provided little reason to expect broad transfer. However, children appeared to encode “living” as a property that applies to all objects or to no object within each superordinate category. Thus, they thought that either all plants or no plants are alive. Children did not show similar consistent categorization for two other biological properties—capacity for growth and need for water—when asked whether the same objects possessed those properties. Why properties are encoded as applying more or less broadly to classes of objects is an important question for future studies on the breadth of children’s learning.

Sources of Change

Microgenetic studies have demonstrated that a wide variety of experiences can evoke change: practice, feedback, direct instruction, social collaboration, requests to explain observations, and so on. In this respect, they are like training studies. Where microgenetic studies go beyond training studies is in the depth of their portrayal of how the particular sources of change produce learning.

Basic Phenomena

Physical maturation and general experience produce substantial changes in many capabilities, even without any specifically relevant experience with the experimental situation (e.g., Shimojo et al., 1986; Spencer et al., 2000; Thelen & Ulrich, 1991). At times, these general changes are as sizeable as those that occur over the same age range among children given directly relevant experience. Thus, in Adolph (1997), control group infants who never had descended down ramps generated strategies and strategy choices equivalent to those of age peers who had encountered the ramps on a weekly basis for several months. Amount of experience at home going up and down stairs and climbing on to and off of furniture (as measured by parental report) appeared to be a crucial factor. Such experience at home was related, above and beyond the effect of age, to individual differences in the infants’ ability to discriminate safe from risky ramps.

Although the practice and feedback obtained by the infants in Adolph (1997) did not enhance their ramp descent skills, problem-solving experience often does produce learning. This is unsurprising when children receive feedback or instruction that guides them toward improved solutions. More surprising, problem-solving experience in the absence of feedback or instruction also often helps children learn. Even when children receive feedback, learning frequently occurs following success rather than failure of existing strategies, a phenomenon first noted by Karmiloff-Smith (1979b) in the context of map drawing and language learning and replicated in many other contexts since then. Learning without negative feedback has been shown for theory of mind inferences (Flynn, 2005), scientific reasoning (Kuhn et al., 1992, 1995; Schauble, 1996), analogical reasoning (Hosenfeld, van den Boom, & van der Maas, 1997; Tunteler & Resing, 2002), memory strategies (Bjorklund, 1988; Coyle & Bjorklund, 1997), and other problem-solving skills. Learning without feedback or instruction often involves generation of new strategies, as well as improved execution of existing strategies. Regardless of whether the activity is a game of 20 questions (Thornton, 1999), a set of mathematical equality problems (Alibali, 1999), a map-drawing task (Karmiloff-Smith, 1979b), or rediscovery of the decimal system following brain injury (Siegler & Engle, 1994), people generate new approaches even without specially designed instruction or failure of existing approaches. Thus, problem solving per se can be a source of change.

Another source of change that has received considerable attention in microgenetic research is social collaborative problem solving. Microgenetic analyses of collaboration have been applied to mother-infant inter-
action (Wertsch & Hickmann, 1987), pairs of 5- to 9-year-olds learning about balance scales (Tudge, 1992; Tudge, Winterhoff, & Hogan, 1996), pairs of first graders learning to write narratives (Jones, 1998; Jones & Pellegrini, 1996), small groups of fourth graders solving mathematical word problems via reciprocal instruction (Taylor & Cox, 1997), pairs of fifth graders learning about decimal fractions (Ellis, Klahr, & Siegler, 1993), pairs of fifth and seventh graders building bridges (Parziale, 2002), pairs of sixth, seventh, and eighth graders solving science reasoning problems (Kuhn & Pearsall, 2000), a classroom of ninth-grade ESL students learning a science curriculum (Gelman et al., 2002), and small groups of adults designing robotic devices (Granott, 1998; Granott et al., 2002). The large amount of overt behavior, both conversations and actions, generated by collaborative problem solving makes such situations ideal for microgenetic analysis.

A particularly interesting finding that has emerged from these studies is that the degree of engagement of the partners is crucial to the effectiveness of learning (Ellis et al., 1993; Forman & MacPhail, 1993; Glachen & Light, 1982; Perret-Clermont, Perret, & Bell, 1991; Tudge, 1992; Tudge et al., 1996). Listening intently to partners’ explanations, requesting clarification of them, and reaching shared understanding strongly influence how much learning occurs.

A number of factors probably contribute to the effects of engagement on learning. Engagement seems likely to reflect interest in the subject matter, general motivation to learn, and the quality of the relationship between or among collaborators.

Engagement also seems likely to be related to a learning process that is powerful—in both collaborative and noncollaborative situations—extracting causal relations. Listening intently, requesting clarifications, and reaching shared understandings may help learners probe deeply enough to understand underlying causal relations within the problems, and such understanding of causal relations may be crucial to learning.

Evidence from studies of individual as well as collaborative learning attests to the crucial role of causal understanding in all kinds of understanding.

Ability to form causal connections among events starts in the 1st year of life (e.g., Kotovsky & Baillearger, 1994). Even 1-year-olds find it easier to learn to reproduce causally coherent sequences of actions than arbitrary sequences (Bauer, Chapter 9, this Handbook, this volume). Thus, ability to explain the causes of events seems to be a basic property of human beings.

Despite this early development, even older children and adults fail to grasp causal relations in many situations in which doing so would be useful. This poses an especially large problem for understanding mathematics and science. Even among adults at elite universities, causal understanding of physical and biological phenomena tends to be extremely shallow (Rozenblit & Keil, 2002).

Somewhat surprisingly, given this poor understanding of causality underlying physical and biological phenomena, microgenetic studies have revealed that people are highly motivated to learn about causal relations. When children expect some physical or biological variables to be causal and others not to be, they generate more experiments regarding the effects of the variables that they expect to be causal (Kuhn et al., 1988, 1992). Both 10-year-olds and adults more effectively learn that particular physical variables are causally related than that they are not related (Schauble, 1996). Children also are reluctant to abandon a belief that a variable exerts a causal influence in favor of the conclusion that the variable is not causal (Kuhn & Pearsall, 1998).

Understanding causal relations is also crucial to learning. Children learn more when actively testing causal hypotheses through self-generated experiments than they do from watching the same experiments generated by other children, where they do not know the hypothesized cause being tested (Kuhn & Ho, 1980). Understanding why a given memory strategy exerts a positive effect is closely related to whether children choose to use the strategy when not required to do so (Paris et al., 1982). In addition, among older children and adults, individual differences in efforts to explain the causal hows and whys in science and math textbooks are closely related to the amount learned (Chi, Bassok, Lewis, Reimann, & Glaser, 1989; Chi, de Leeuw, Chiu, & LaVancher, 1994; Nathan, Mertz, & Ryan, 1994).

How does causal understanding enhance learning? One path is through avoiding trial and error and limiting searches for new approaches to plausible alternatives. For example, understanding how counterbalancing produces stable physical structures allows school age children to construct superior new bridges if their initial attempts collapse (Thornton, 1999). Similarly, understanding the goals that successful addition strategies must meet allows preschoolers to discover effective addition strategies without any trial-and-error (Siegel & Crowley, 1994). Conversely, misunderstanding causal relations often produces distorted recollections of experiments and results, which impedes learning (Kuhn
et al., 1995). And as noted earlier, causal relations, once learned, are more memorable than arbitrary relations (Bauer, Chapter 9, this Handbook, this volume). Thus, causal understanding motivates, guides, and maintains learning.

Influences of Child and Environment

Although infants and toddlers sometimes identify causal relations, and although adults fairly often fail to identify such relations, the frequency with which people identify causal connections on any given task generally increases with age. In scientific reasoning contexts, adults consistently are superior to older children, and older children are superior to younger ones, in learning which variables exert a causal influence (Chen & Klahr, 1999; Kuhn et al., 1992, 1995; Schauble, 1996). The same age trends are apparent on other types of problem-solving tasks; for example, on the previously mentioned bridge building task that required understanding of the causal role of counterbalancing, 10% of 5-year-olds, 40% of 7-year-olds, and 70% of 9-year-olds succeeded (Siegler, 1999).

The pervasive positive effect of understanding causal relations raises the issue of whether encouraging children to seek causal understanding improves their learning. Numerous experiments indicate that the answer is “yes.” Asking 5-year-olds to explain why an experimenter advanced the number conservation answer that she did leads to greater learning than does asking peers to explain their own answers or simply providing feedback (Siegler, 1995). Asking 7-year-olds to explain why some representations are better than others leads to their subsequently generating better representations themselves (Triano, 2004). Asking 5- to 9-year-olds to explain why a balance scale rotated as it did leads to greater learning than just having them observe the movements (Pine & Messer, 2000). Asking 12-year-olds to explain statements within eighth-grade biology textbooks enhances their learning, even relative to having them read the textbook twice (Chi et al., 1994). Asking first through fourth graders to explain both why correct answers are correct and why incorrect answers are incorrect leads to greater learning of mathematical equality and sinking objects problems than does asking peers to explain the correct answer alone or to explain their own reasoning (Siegler, 2002; Siegler & Chen, in preparation). The same has been found in classroom settings; asking children to explain why wrong answers are wrong as well as why right answers are right is more effective instructionally than just modeling the correct answer. The difference is particularly large on problems fairly far removed from the original problem (Taylor & Cox, 1997). This tendency for understanding of causal relations to be especially important on transfer problems has also appeared in laboratory studies of other tasks (Alibali, 1999; Crowley & Siegler, 1999; Rittle-Johnson & Alibali, 1999; Siegler, 2002).

Theoretical Implications and Questions

Why does being asked to explain observations enhance learning, and why does being asked to also explain why wrong answers are wrong enhance learning further? The phenomena are not attributable to time on task; encouragement to explain observations heightens learning even when time on task is controlled (Aleven & Koedinger, 2002; Chi et al., 1994; Renkl, 1997). At a general level, self-explanation seems to work by increasing learners’ depth of processing. One way in which it does this is to increase the likelihood of learners generating any explanation. People often accept observations without asking “why.” However, when people are explicitly asked, “Why do you think that happened?” they are more likely to think about the observation deeply enough to generate an explanation or, in Chi’s (2000) formulation, to repair their mental model. Constructing such an explanation is often harder than it might appear; learners who generate incorrect answers and who then are asked to explain the correct answer often initially respond by saying, “I don’t know” (Flynn, submitted; Siegler, 1995). However, in these same studies, increasing numbers of children eventually did generate the correct explanation, and it became the most frequent approach.

A related process through which encouragement to explain may enhance learning is by increasing the persistence of explanatory efforts. In Siegler’s (2002) study of mathematical equality, the third- and fourth-grade participants took around 11 seconds on Trial 1 to generate an answer to the $A + B + C = \_\_\_\_\_\_\_\_\_ + C$ problem that they were presented. After being asked to explain both why the right answer was right and why the wrong answer was wrong, children in that condition took much longer to generate answers to the same type of problems on the next few trials; the mean solution time rose to 22 seconds on Trial 2 and 25 seconds on Trial 3. This extra time was not attributable to the correct strategy that they eventually learned inherently taking longer; after two more trials, their times returned to
the original level of around 11 seconds. Peers who received feedback on the same problems but who were not asked to generate explanations did not show this pattern of increasing and then decreasing solution times; their mean times remained around 11 seconds on all trials. Instead, the extra time taken by children who were asked to explain correct and incorrect answers seemed to reflect a deeper search for a strategy that could generate correct answers.

Consistent with this explanation, although children in both feedback and self-explanation groups of Siegler (2002) generated ways of solving the problems correctly by the end of the training session, the discoveries differed in quality. Most children in the feedback group generated a strategy that yielded correct answers on the problems that were presented \( (A + B + C = \ldots + C \text{ problems}) \); they simply added \( A + B \). This strategy worked on these problems, but it did not generalize beyond them. In contrast, most children who were asked to explain both correct and incorrect answers relied on one of two more advanced and general approaches: these children either computed what they needed to add to \( C \) to equalize the values on the two sides of the equal sign or subtracted \( C \) from both sides. The result was that on the posttest, the percent correct on problems of the type presented during training did not differ for the two groups, but there were substantial differences on transfer problems such as \( A + B + C = \ldots + D \), on which the more sophisticated strategies would work and the less sophisticated one would not. Thus, the effectiveness of encouragement to explain observations also is probably due in part to such encouragement producing deeper searches of existing knowledge.

A third mechanism through which self-explanation may exercise its effects is by decreasing the strength of existing, incorrect ways of thinking. Evidence for such a weakening process again was found in Siegler (2002). The frequency of children’s predominant incorrect strategy, adding \( A + B + C \), fell much more rapidly in the group asked to explain both why wrong answers were wrong and why right answers were right than in a group asked only to explain why right answers were right. On the initial trial, before feedback or requests for explanations, 80% of children in both groups used the \( A + B + C \) approach. On the next trial, 50% of children in the feedback group continued to use this approach, but only 25% of children in the self-explanation group did. As emphasized throughout this chapter, incorrect approaches often persist for substantial periods of time, even after superior approaches are also known; instructional approaches that undermine the incorrect approaches, in this case by having children explain why they are incorrect, can speed learning by undermining the logic that supports them and thus decreasing their appeal.

RELATIONS BETWEEN LEARNING AND DEVELOPMENT

The relation between short-term and long-term change (aka learning and development; microdevelopment and macrodevelopment; change at short and long time scales) is among the enduring issues in developmental psychology. Classical theorists have taken sharply conflicting stances regarding the issue. Werner (1948, 1957) and Vygotsky (1934/1962) viewed short-term change as a miniature version of long-term change, generated by similar underlying processes and characterized by identical sequences of qualitatively distinct stages. Learning theorists such as Kendler and Kendler (1962) also viewed the two as fundamentally similar, but unlike Werner and Vygotsky, they viewed both short-term and long-term change as proceeding through gradual incremental processes with no qualitatively distinct stages. Piaget (e.g., 1964, 1970) expressed a third perspective; he viewed the two types of change, which he referred to as learning and development, as fundamentally dissimilar. In his view, development created new cognitive structures; learning merely filled-in specific content.

The relation of short-term to long-term change continues to be discussed by contemporary theorists: dynamic systems (e.g., van Geert, 1998), neo-Piagetian (e.g., Case, 1998), and information processing (e.g., Elman et al., 1996). There appears to be a broad consensus that changes over short and long time periods resemble each other, but much less agreement as to the level of detail at which the resemblance holds. Some investigators have concluded that the similarity is a deep one; for example, Thelen and Corbetta (2002) wrote:

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. In other words, the principles underlying behavioral change work at multiple time scales. (p. 60)

Other investigators (e.g., P. H. Miller & Coyle, 1999; Pressley, 1992) have concluded that the degree of similarity between microgenetic and age-related change is
uncertain, both at the level of the descriptive course of change and at the level of underlying mechanisms. They also have noted that the conditions used to elicit change in microgenetic studies often differ from those that elicit it in the everyday environment. Even when the eliciting events are basically similar, the higher density of relevant experiences and the more consistent feedback in the laboratory setting could result in the changes being quite different in their specifics. These issues led P. H. Miller and Coyle (1999) to conclude: “Although the microgenetic method reveals how behavior can change, it is less clear whether behavior typically does change in this way in natural settings” (p. 212).

After noting this uncertainty regarding the precision of the resemblance between microgenetic and age-related change, Fischer and Granott (1995) and Kuhn (1995) suggested a solution: Set up direct comparisons with identical populations, methods, and measures of the changes observed in microgenetic studies and those observed in cross-sectional and long-term longitudinal studies. To provide such a direct comparison, Siegler and Svetina (2002) combined cross-sectional and microgenetic designs within a single experiment. In the cross-sectional part, they presented 6-, 7-, and 8-year-olds with standard matrix completion and conservation problems of the type used by Inhelder and Piaget (1964) and Piaget (1952). Then, a randomly chosen half of 6-year-olds were presented four sessions of feedback and self-explanation prompts on matrix completion problems, followed 2 months later by a posttest on matrix completion and conservation. The other half of the 6-year-olds did not receive the four feedback-and-self-explanation sessions, and thus served as a control group.

The overall magnitude of change among children in the microgenetic condition, as indicated by the percent correct answers, proved comparable to the magnitude of the change between ages 6-years and 7-years among children in the cross-sectional part of the study. This comparability of overall change allowed a reasonable comparison to be made of the detailed patterning of changes on 11 measures of performance.

Microgenetic and age-related changes were similar on 10 of the 11 measures. On five of these measures, both groups showed significant changes, and on another five, neither group did. The specificity of many of the matches was quite striking. For example, there were changes over both sessions and years in number of answers correct on the size dimension, but no changes over sessions or years in the number of explanations that mentioned size. Qualitative aspects of change were also similar. For example, children in both groups produced the same predominant error; in both cases, it accounted for about 70% of total errors. The learning of children in the microgenetic condition also was highly stable over time and generalized to the conservation tasks, qualities that Piaget identified as defining characteristics of developmental change. Thus, at least in this case, microgenetic change proved extremely similar to age-related changes that occurred without any experimental manipulation.

Similar broad parallels in the path of microgenetic and age-related change have been found on balance scale, sort-recall, mathematical equality, addition, language development, map drawing, false belief, and many other problems (Alibali & Goldin-Meadow, 1993; Chleto & De Lisi, 1991; Flynn et al., 2004; Grupe, 1998; Karmiloff-Smith, 1979a; Schlagmüller & Schneider, 2002). To cite one example, experience performing a selective attention task produced the same inverted U-shaped function in amount of private speech as emerged between ages 3 and 5 years without such experience (Winsler, Díaz, & Montero, 1997). To cite another example, the same type of balance scale rule progressions that emerged in cross-sectional studies between ages 5 and 8 years emerged over trials within a single session when 5-year-olds were given feedback and asked to explain their observations (Siegler & Chen, 1998).

Clearly, microgenetic and age-related change will not always be so similar. When direct instruction is provided, people may often follow paths different than the ones they would otherwise have followed. To illustrate, children who produce gesture-speech mismatches while solving mathematical equality problems usually progress toward correct gesture and speech if given direct instruction; however, they usually regress toward incorrect gesture and speech in the absence of instruction (Goldin-Meadow & Alibali, 2002). Highly directive instruction also can alter the path of change in another way; it at times produces immediate consistent use of the correct approach and thus eliminates intermediate approaches that would otherwise have appeared (Opfer & Siegler, 2004). Nonetheless, when microgenetic studies do not involve directive instruction, microgenetic and age-related changes tend to be highly similar. As Kuhn (2002) noted:

Microgenetic analysis achieves a reintegration of learning and development as processes that have fewer differences
than they do commonalities. . . . Rather than standing in opposition to the study of development, fine-grained studies of learning illuminate, indeed are essential to understanding, the more macro-level phenomena of development. (p. 111)

CHANGE MECHANISMS

Deeply understanding how change occurs is the holy grail of developmental psychology: a profound goal, never fully attained, probably not attainable, but worth pursuing nonetheless. One reason for the impossibility of fully succeeding is that change processes are inherently unobservable; they can only be inferred from behavioral observations at different points in time. Another reason is that such mechanisms can be described at multiple levels that vary in specificity (maturation, improved working memory, automatization), time gain (years, seconds, milliseconds), and system (behavioral, computational, neural). Progress in understanding mechanisms at each level of specificity, time gain, and system inevitably raises questions about the other levels.

Despite these inherent limits on understanding change processes, the detailed descriptions of change yielded by microgenetic analyses can move us toward the goal, both by suggesting candidate mechanisms that are consistent with the wide range of data yielded by such studies and by ruling out alternatives that are inconsistent with them. One good example comes from studies of gesture-speech mismatches. Alibali and Goldin-Meadow (1993) hypothesized on the basis of microgenetic data that gesture-speech mismatches reflected competition between representations, and that simultaneous activation of competing representations would require more cognitive resources than would activating a single idea. To test this hypothesis, Goldin-Meadow, Nusbaum, Garber, and Church (1993) asked children to remember a set of unrelated words while they solved mathematical equality problems. All of the children generated incorrect mathematical equality strategies in speech, but some generated correct strategies in gesture. Strikingly, the children who generated correct strategies in gesture, and who thus were more knowledgeable about mathematical equality, did less well on the concurrent task of remembering words. This evidence strongly suggested that simultaneous activation of competing representations is one mechanism underlying gesture-speech mismatches.

Microgenetic studies also can illuminate neural mechanisms that underlie learning. For example, Haier et al. (1992) found that as college students learned to play the video game Tetris, they reduced their overall glucose metabolism, with the decrease being greatest in brain areas that did not seem essential for playing the game. The largest changes in glucose metabolism were seen among the participants who showed the largest improvements in game playing skill.

The detailed data yielded by microgenetic studies also constrain mechanistic accounts and raise process-level issues that otherwise would not arise. One such case involves learning in the face of success. Microgenetic studies of map drawing, counting, balance scales, arithmetic, sort-recall, and selective attention tasks have shown that strategy discoveries follow success as well as failure (Blöte et al., 1999, 2004; Karmiloff-Smith, 1979b; P. H. Miller & Aloise-Young, 1995; Siegler & Jenkins, 1989). The observation has created a need for models that, unlike connectionist and many symbolic models, generate new approaches without error detection.

Another way in which microgenetic data can help specify mechanisms is by revealing relations among multiple changes. In one illustrative study, Robinson and Mervis (1998) sampled a single child’s language development on a daily basis between the ages of 11 and 25 months. Of particular interest were their findings concerning the relation between vocabulary size and grammatical development. They found that the precursor mechanism proposed by van Geert (1991) fit their data. This mechanism links two asynchronously developing capabilities: a predecessor (earlier developing) capability and a successor (later developing) capability. The predecessor (in this case, vocabulary) needs to reach a critical value before the successor (in this case, use of plurals) begins to emerge. The emergence of the successor capability initially increases the rate of development of the predecessor. Over time, however, the successor becomes a competitor for resources with the predecessor, and development of the predecessor slows. Finally, the successor reaches an asymptotic level and stops competing for resources, and the rate of development of the predecessor again increases. As in the other examples in this section, the microgenetic data were critical for linking this mechanism to the change being explained.

Microgenetic studies can be particularly useful for enhancing understanding of change mechanisms when they are part of a back-and-forth process involving them,
formal modeling, and traditional cross-sectional and longitudinal empirical studies. Research on the development of basic arithmetic illustrates this process.

A number of early cross-sectional studies indicated that preschoolers and young elementary school children use varied strategies to solve simple addition problems (e.g., Fuson, 1982). As noted earlier, preschoolers’ most common approach is the sum strategy, which involves putting up fingers on one hand to represent the first addend, putting up fingers on the other hand to represent the second addend, and then counting all of the fingers. First and second graders’ most common approach is the min strategy, which involves counting up from the larger addend.

This information provided the basis for Siegler and Jenkins’ (1989) microgenetic study of discovery of the min strategy. Children of the age just prior to when the discovery would usually be made (4- and 5-year-olds) were presented 20 to 30 brief sessions of experience with addition. The study yielded eight main findings, which also could be viewed as eight main constraints that a satisfactory model of discovery of the min strategy would need to meet: (1) Almost all children discovered the min strategy; (2) all children used varied strategies both before and after the discovery; (3) the shortcut sum strategy, which incorporated some aspects of the sum strategy and some aspects of the min strategy, usually was generated shortly before discovery of the min strategy; (4) discoveries often occurred in the context of success rather than failure; (5) generalization of the min strategy was slow; (6) presenting challenge problems on which the min strategy was particularly advantageous hastened generalization; (7) strategy choices were at all times responsive to problem characteristics; and (8) children discovered the min strategy without any trial and error.

This last finding was particularly intriguing. Despite solving between 140 and 210 problems and generating a number of novel addition strategies, none of the children ever generated an illegal strategy. It was not that no illegal strategies were possible; for example, children could have added the first addend twice and ignored the second one, or added the first addend to the second one and then added the second one again. This raised the question of how children were able to invent legal strategies without any trial and error with illegal strategies.

To address the question, Siegler and Jenkins hypothesized that even before children discover the min strategy, they possess a goal sketch, a conceptual structure that indicates the goals that a legal strategy must meet. The goal sketch for addition indicates that legal strategies must include procedures for quantifying each addend and combining the two addends into a single answer.

This hypothesis motivated Siegler and Crowley (1994) to perform a new empirical study to test whether children possess such a goal sketch even before they discover the min strategy. They asked 5-year-olds, some who already used the min strategy and some who did not, to judge the smartness of three addition procedures that a puppet executed: the sum strategy, which all of the children already used in their own problem solving; the min strategy, which some children used and some did not; and counting the first addend twice, which none of the children used. The question was whether children who did not yet use the min strategy would view it as smarter than counting the first addend twice, which they also did not use. It turned out that they viewed the min strategy as much smarter than counting the first addend twice; in fact, they viewed the min strategy as being slightly smarter than the strategy they used most often, the sum strategy. This finding led to the conclusion that children possess conceptual understanding of addition akin to the goal sketch before they discover the min strategy and that this understanding helps them avoid trial and error in the discovery process.

These data from Siegler and Crowley (1994), together with the prior cross-sectional and microgenetic findings, provided crucial constraints on a computer simulation of discovery of the min strategy (Shrager & Siegler, 1998). The model began with two strategies—retrieval and the sum strategy—and was presented addition problems like those in Siegler and Jenkins (1989). Through solving these problems, the model learned which types of strategies work best in general and on particular types of problems. The mechanisms that produced learning and discovery within this model are illustrated schematically in Figure 11.4.

As shown at the top of Figure 11.4, within this model when strategies are used to solve problems, the process yields information about the answers to the problems, as well as the speeds and accuracies characteristic of the strategies and the problems. The model learns which strategies are most effective in general and which work best on problems with specific features, as well as which work best on particular problems. Each problem-solving effort also yields a trace of the processing per-
Siegler and Araya (in press) recently expanded the model to simulate Siegler and Stern’s (1998) findings regarding how children generate an arithmetic insight. That model produces variations in performance under different experimental conditions, regressions between sessions, learning within sessions, patterns of overgeneralization and undergeneralization, and both conscious and unconscious strategy discoveries. Of particular interest, the model indicates that what looked at a behavioral level to be five distinct strategies is at a mechanistic level only two strategies combined in different ways and with different levels of activation. As these examples suggest, combining microgenetic data, data on changes with age, and formal modeling techniques offers considerable promise for enhancing understanding of how children learn.

**Conclusion**

The research summarized in this chapter supports the view that children’s learning is inherently a process of variability, choice, and change. This characterization is not unique to children’s learning; indeed, mechanisms that generate variability, choice, and change are essential to all adaptive systems, from plants and animals to cultures and corporations. The specific mechanisms that produce these characteristics vary greatly, but the characteristics themselves are invariant.

Microgenetic studies have revealed numerous aspects of how variability, choice, and change operate in the context of children’s learning. Such studies have revealed that children are constantly generating new variants, not just during delimited transition periods and not just when existing approaches fail, but at all times. They also have revealed that the varying approaches that children generate are constrained by conceptual understanding, rather than being a process of trial and error. They also have revealed that choices among variants are surprisingly adaptive from the beginning of learning, that this is true even in infancy, and that the choices become yet more adaptive with experience in the specific domain. And the research also has revealed that the uptake of even the best new approaches often is slow and halting, and that this is true even when children can explain why the new approach is superior to alternatives.

All of these characteristics seem to be true of what has traditionally been called “development” as well as what has traditionally been called “learning.” Indeed,
the distinction between development and learning seems increasingly artificial, given that both are processes of variability, choice, and change, and that studies of age-related changes and learning reveal so many empirical commonalities. However, this may only be how things appear at present. Detailed analysis of the mechanisms that operate over shorter and longer time periods may reveal more substantial differences than are currently evident. Mechanistic models of short-term change, guided by and constrained by microgenetic data, are being created in increasing number. Testing whether the mechanisms that produce changes within these models can also account for long-term changes—and determining how, if at all, they need to be changed to do so—promises to be a particularly exciting frontier for the new field of children’s learning.

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