Cognitive Variability: A Key to Understanding Cognitive Development

Robert S. Siegler

Among the most remarkable characteristics of human beings is how much our thinking changes with age. When we compare the thinking of an infant, a toddler, an elementary school student, and an adolescent, the magnitude of the change is immediately apparent. Accounting for how these changes occur is perhaps the central goal of researchers who study cognitive development.

Alongside this agreement about the importance of the goal of determining how change occurs, however, is agreement that we traditionally have not done very well in meeting it. In most models of cognitive development, children are depicted as thinking or acting in a certain way for a prolonged period of time, then undergoing a brief, rather mysterious, transition, and then thinking or acting in a different way for another prolonged period. For example, on the classic conservation-of-liquid quantity problem, children are depicted as believing for several years that pouring water into a taller, thinner beaker changes the amount of water; then undergoing a short period of cognitive conflict, in which they are not sure about the effects of pouring the water; and then realizing that pouring does not affect the amount of liquid. How children get from the earlier to the later understanding is described only superficially.

Critiques of the inadequacy of such accounts have been leveled most often at stage models such as Piaget's. The problem, however, is far more pervasive. Regardless of whether the particular approach describes development in terms of stages, rules, strategies, or theories; regardless of whether the focus is on reasoning about the physical or the social world; regardless of the age group of central interest, most theories place static states at center stage and change processes either in the wings or offstage altogether. Thus, 3-year-olds are said to have nonrepresentational theories of mind and 5-year-olds representational ones; 5-year-olds to have absolute views about justice and 10-year-olds relativistic ones; 10-year-olds to be incapable and 15-year-olds capable of true scientific reasoning. The emphasis in almost all developmental theories has been on identifying sequences of one-to-one correspondences between ages and ways of thinking or acting, rather than on specifying how the changes occur.

If developmentalists are so interested in change processes, why would the topic be given such cursory treatment in most contemporary theories? Part of the problem is that studying change is inherently difficult. It poses all the conceptual and methodological demands of studying performance at any one time, and imposes the added demands of determining what is changing and how the change is being accomplished.

An additional part of the difficulty, however, may be self-imposed. In our efforts to describe differences among age groups in as simple, dramatic, and memorable terms as possible, we may unwittingly have made understanding change more difficult than it needs to be. In particular, portraying children's thinking and knowledge as monolithic for several years at a time creates a need to explain the wide gulfs between the successive hypothesized understandings—even though such gulfs may not exist. The typical depictions make change a rare, almost exotic, event that demands an exceptional explanation. If children of a given age have for several years had a particular understanding, why would they suddenly form a different understanding, and why would they regularly form it at a particular age? The problem is exacerbated by the fact that for many of the competencies of interest, generally relevant experience is available at all ages and specifically relevant experience at none. Children see liquids poured into containers of different dimensions at all ages—and are not ordinarily told at any age that the amount of liquid remains the same after pouring as before. Why, then, would they consistently have one concept of liquid quantity conservation at age 5 and a different one at age 7?

Recognition of the unwelcome side effects of the one-to-one depictions of cognitive growth has led to a new generation of research that focuses directly on changes in children's thinking. This research has documented large-scale variability in children's thinking and suggests that the variability contributes directly to cognitive growth.

**Pervasive Variability**

Variability in children's thinking exists at every level—not just between children of different ages, or between different children of the same age, but also within an individual solving a set of related problems, within an individual solving...
the same problem twice, and even within an individual on a single trial.

Variability Within an Individual Solving Related Problems

Detailed analyses of tasks on which one-to-one correspondences between age and way of thinking have been postulated indicate that children's thinking is generally much more variable than past depictions have suggested. To cite an example from language development, rather than young children passing through a stage in which they always overregularize past tense forms (e.g., saying "goed" and "eeted" rather than "went" and "ate"), children at all ages between 2½ and 5 years produce substantial numbers of overregularized forms and substantial numbers of correct ones. The variability throughout this age range is present for a single child followed throughout the period, as well as for groups of children sampled at a single age. Adding to the variability, children often produce more than one incorrect form of a given verb; on different occasions, a given child will say, "I ate it," "I eated it," and "I ated it." 1

Similar variability has been found in the development of memory strategies. Contrary to the widely cited model that 5-year-olds do not rehearse and 8-year-olds do, trial-by-trial assessments indicate that the majority of children of both ages sometimes do and sometimes do not rehearse. 2 The percentage of trials on which they rehearse increases with age, but, again, there is variability throughout the age range.

Conceptual development evidence the same pattern. Despite claims that 5-year-olds think of number conservation solely in terms of the lengths of the rows, trial-by-trial assessments indicate that most 5-year-olds sometimes rely on the lengths of the rows, sometimes rely on the type of transformation, and sometimes use other strategies such as counting or pairing. 3 Again, the frequency of reliance on these ways of thinking changes with age, but most 5-year-olds' judgments and verbal explanations indicate several different ways of thinking about the concept.

Development of problem-solving skills provides yet more evidence for such within-subject cognitive variability. Contradicting models in which preschoolers are said to use the sum strategy (counting from 1) to solve simple addition problems and in which first through third graders are said to use the min strategy (counting from the larger addend, as when solving 3 + 6 by counting "6, 7, 8, 9") to solve them, children of all these ages use a variety of strategies. In one study, most children presented a set of addition problems used at least three different strategies on different problems, and most children examined in a more extensive microelectrode study used at least five distinct strategies. 4

Variability Within an Individual Solving a Single Problem Twice

The variability within individual children cannot be reduced to children using different strategies on different problems. Even presented the identical problem twice within a single session, or on 2 successive days, children use different strategies on roughly one third of the pairs of trials in addition, time-telling, and block-building tasks. 5 This variability within individuals within problems cannot be explained by learning; in these studies, children used the strategy that appeared more advanced almost as often for the first presentation of a problem as for the second (roughly 45% vs. 55%).

Variability Within a Single Trial

In the limiting case, variability has been found even within an individual solving a particular problem on a single trial. This type of variability has been reported by investigators interested in the relation between children's hand gestures and verbal explanations. In these studies, children often express one type of understanding through the gestures and a quite different understanding through the explanations. 6 For example, on number conservation problems, children may express a reliance on relative lengths of the rows in their hand gestures, while at the same time verbally expressing reliance on the type of transformation, or vice versa.

These findings suggest that cognitive change is better thought of in terms of changing distributions of ways of thinking than in terms of sudden shifts from one way of thinking to another. The types of descriptions of change that emerge from such analyses are illustrated in Figures 1 and 2. Figure 1 shows changes in 3 children's addition strategies over a 3-month period; 4 Figure 2 shows changes in a child's map-drawing strategies over a 2-year period. 7 Similar changes in distributions of strategies have been found in studies of conceptual understanding, memory strategies, problem solving, and language. In all these domains, cognitive development involves changing distributions of approaches, rather than discontinuous movements from one way of thinking to another.

VARIABILITY AND COGNITIVE CHANGE

Variability is not just an incidental feature of thinking; it appears to play a critical role in promoting cognitive change. Several types of evidence converge on this conclusion. One comes from observations of children in the process of discovering new strategies. Both the trials immediately before a discovery and the
trial on which the discovery is made frequently involve especially variable behavior—disfluencies, unclear references, long pauses, and unusual gestures. A second type of empirical evidence linking variability to cognitive change involves analyses of which children are most likely to make discoveries. Children whose verbal explanations and gestures reflect different initial misunderstandings of number conservation and of numerical equivalence problems (a + b + c = __ + c) are more likely to make discoveries subsequently than are children whose explanations and gestures reflect the same initial misunderstanding. Similarly, children whose pretest explanations reflect varied ways of thinking are more likely to learn from instruction regarding the meaning of the equal sign in mathematics than are children whose pretest explanations reflect crisp, specific misunderstandings.

A different type of evidence for the contribution of variability to cognitive change comes from formal models of development. Theorists who differ in many particular assumptions have found that modeling change requires both mechanisms that produce variability and mechanisms that produce adaptive choices among the variants. Connectionist models of development are based on connection strengths among processing units varying at all points in learning, from initial, randomly varying strengths to final, asymptotic levels; change occurs through redistributions of the varying connection strengths. Dynamic systems models also treat variability as a fundamental property of development; they aim to explain how local variability gives rise to global regularities. Similarly, recent symbolic-processing models of development focus on how varying strategies, analogies, and other higher order units come to be used increasingly in the situations in which they are most effective. At a less formal level, operant condi-

Fig. 1. Changes in distributions of addition strategies of 3 children over roughly 30 sessions conducted over a 3-month period. Notice the variability that is present within each child’s performance within each block of sessions, as well as the changes in distributions of strategy use over the course of the study (data from Siegler and Jenkins).
tioning models, evolutionary based models, and generate-and-test models are all based on the assumption that change occurs through selection processes operating on omnipresent, spontaneously produced variability in behavior.9

A striking empirical finding about the variability in children's thinking, and one that is important for its ability to contribute to cognitive development, is the constrained quality of the variations that children generate. Far from conforming to a trial-and-error model, in which all types of variations might be expected, the new approaches that children attempt consistently conform to the principles that define legal strategies in the domain (except when children are forced to solve problems for which they do not possess any adequate strategy). For example, in a 30-session study of preschoolers' discovery of new addition strategies, none of the children ever attempted strategies that violated the principles underlying addition.4 They invented legitimate new strategies, such as the min strategy, but never illegitimate ones, such as adding the smaller addend to itself or counting from the larger addend the number of times indicated by the first addend. The question is how they limit their newly generated strategies to legal forms.

One possibility is that even before discovering new strategies, children often understand the goals that legitimate strategies in the domain must satisfy. Such understanding would allow them, without trial and error, to discriminate between legitimate new strategies that meet the essential goals and illegitimate strategies that do not. A very recent study revealed that children possessed such knowledge in both of the domains that were examined—simple addition and tic-tac-toe.10 In simple addition, children who had not yet discovered the min strategy nonetheless judged that strategy (demonstrated by the experimenter) to be as smart as the strategy they themselves most often used—counting from 1—and significantly smarter than an equally novel but illegitimate strategy that the experimenter demonstrated. In tic-tac-toe, children rated a novel strategy that they did not yet use—forking—as even smarter than the strategy they themselves usually employed—trying to complete a single row or column. Ability to anticipate the value of untried strategies may promote cognitive growth by filtering out unpromising possibilities and thus channeling innovations in potentially useful directions.

CONCLUSIONS

Thinking is far more variable than usually depicted. In the past, researchers have usually ignored such variability or viewed it as a bother. This stance has led to subjects being given practice periods, not so the especially variable behavior in those periods can be studied, but so that it can be discarded, in order that it not obscure the more orderly patterns in later performance. When such variability has been explicitly noted at all, it has usually been viewed as an unfortunate limitation of human beings, a kind of design defect, something to be overcome through practice. Computers, robots, and other machines not subject to this flaw can perform many tasks more accurately than people can. Presumably, people's performance would also be enhanced if it were less variable.

This view of variability as detracting from efficient performance misses at least half the story, though. The variability of cognition and action allows us to discover a great deal about the environments toward which the thinking and action are directed. Our difficulty in reproducing the way we pronounced a word in an unfamiliar foreign language may lead to some even less adequate pronunciations in the short run, but in the longer run may lead us to generate and then learn better pronunciations. Likewise, our inability to give a colloquium in the same words twice, even when we want to, may lead to some parts being less clear than in the best of our previous presentations, but it also allows us to observe audience reaction to new lines of argument and to learn which ones are best received. In general, cognitive variability may lead to performance never incorporating on any one occasion all the best features of previous performance, but also may be critical to our becoming increasingly proficient over time.

If cognitive variability does indeed facilitate learning, it would be adaptive if such variability were most pronounced when learning, rather than efficient performance, is most important—that is, in infancy and early childhood. This appears to be the case. Across many domains, expertise brings with it decreasingly variable performance. To the extent that young children are "universal novices," their lack of expertise alone would lead to their performance being more variable than that of older children and adults. A number of cognitive neuroscientists have hypothesized that above and beyond such effects of practice, the
process of synaptogenesis, which results in children from roughly birth to age 7 having far more synaptic connections than older children and adults, may contribute both to the high variability of early behavior and to young children's special ability to acquire language, perceptual skills, and other competencies under abnormal organic and environmental conditions. That is, young children's greater variability at the neural level seems to allow them to learn useful behaviors under a greater range of circumstances. The general lesson seems to be that explicitly recognizing the great variability of infants' and young children's thinking, and attempting to explain how it is generated and constrained, will advance our understanding of the central mystery about cognitive development—how change occurs.

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