Cognitive variability

Robert S. Siegler

Department of Psychology, Carnegie Mellon University, USA

Abstract

Children's thinking is highly variable at every level of analysis, from neural and associative levels to the level of strategies, theories, and other aspects of high-level cognition. This variability exists within people as well as between them; individual children often rely on different strategies or representations on closely related problems presented close in time. Recognising such variability can help us both describe development more accurately and better explain how cognitive change occurs.

Introduction

Children's thinking is far more variable than has usually been recognized. This variability is omnipresent, occurring at all ages, in all domains, and at all points in learning. The variability is evident 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. It is present not only between different people, where it has long been recognized, but also within a single person solving the same problem at two points close in time, and even within an individual's performance on a single trial. Recognizing this variability is important not only for accurately describing development but also for understanding cognitive change. The remainder of this article discusses evidence for these assertions and identifies unresolved issues that seem likely to be important in the coming years.

Prevalence of within-child variability

The advent of video recording, eye movement, and brain imaging technologies has allowed detailed analyses of performance on individual trials, which in turn has allowed fine-grain analyses of variability in individual children's thinking. Results of these analyses indicate that 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.

Toddlers' thoughts and actions are similarly variable. Cicin-Schindler 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 give it to them.

Among the toddlers, 74% used at least three strategies.

Comparable variability has been found in studies of preschoolers. Most 3- and 4-year-olds use multiple selective attention strategies (Miller & Aloise-Young, 1995), most 4-year-olds use multiple strategies to solve analog problems (Tunteler & Resing, 2002) and false belief problems (Flynn, O'Malley & Wood, 2004); 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. 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. Scharber (1996) found that in the course of conducting science experiments, fifth graders and adults changed their minds about the causal status of features an average of 14 times. 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 to the next (Coyle & Bjorklund, 1997; Kuhn & Phelps, 1982; Tunteler & Resing, 2003). Illustratively, Miller and Adams-Young (1985) found that 47% 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 the child's performance became worse in all of these studies—but the progress reflects a back and forth competition rather than a forward march.

The trial-to-trial variability is present even when the same problem is presented on two days close in time. These changes, like those on successive trials, often reflect surprisingly even balance between improvements and regressions. Siegler and Stravel (1984) found that 47% of changes of level of basic addition strategies on the same problem were in a negative direction, and Siegler and McGilly (1987) found that 47% of changes of level of strategies for telling a particular time on a conventional clock were in a negative direction. In these cases and others, performances outnumbered regressions, but the difference was smaller than might have been expected.

Cognitive variability also has been demonstrated within a single trial. 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 (Alcaubis, 1999; Church & Goldin-Meadow, 1986; Perry & Elder, 1997). For example, in Church's (1999) study of number conservation, slightly more than half of children generated gesture-speech mismatch on at least half of the problems. When such mismatches occur, children typically express more advanced understanding in gesture than in speech for example, they might imply 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. Thus, cognitive variability is present at times within a single trial as well as on separate exposures to the same problem.

Significance of within-child variability

The fact that substantial within-child variability exists does not necessarily mean that such variability is important. Some traditional approaches have recognized the existence of within-subject variability but have treated it as a nuisance to be minimized—error variance. Recent 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

Perhaps the strongest evidence for the importance of cognitive variability is that it predicts subsequent learning. For example greater initial variability of strategy use often predicts greater learning. This relation has been documented with numerous types of variability in numerous content areas. Number of strategies used by each child or adult on a problem is highly correlated with subsequent learning on number conservation, sort-recall, and gear problems (Coyle & Bjorklund, 1997; Siegler, 1995; Perry & Elder, 1997). Use of multiple strategies on a single trial (as opposed to over the entire set of problems) predicts learning on mathematical representation (Tajumura, 2001), taxonomic memory (Schlaugmüller & Schneider, 2002), and number conservation problems (Siegler, 1995). Number of different explanations and arguments that a child advances in support of a given explanation predicts the child's learning of number conservation (Church, 1999). Progressing through a single state, in which gestures and speech express different understandings, predicts generalization to a novel task (Goldin-Meadow & Azbal, 2002).

Not all types of variability are positively related to learning. Coyle (2001) examined five measures of variability or sort-recall tasks, a type of memory problem on which multiple strategies can be used within a given trial. The measures were 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 from eight sort-recall experiments indicated that these measures loaded on two main factors: strategy diversity and strategy change. The first measure 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 change, 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 challenge for future research.

Significance for analyzing change

Accurately assessing within-child variability allows more precise theoretical analyses of thinking and learning than
would otherwise be possible. For example, trial-by-trial assessment of strategies allow researchers to analyze the contributions to learning of four component processes: acquisition of new strategies, increasing use of the most advanced existing strategies, increasingly efficient execution of strategies, and improved choice among strategies. Lomaitis and Siegler's (1995) study of French second graders' increasing proficiency in single digit multiplication illustrates how this taxonomy can be used to analyze learning. The children's strategy use, accuracy, and speed were observed three times during the year: one week, three months, and five months after the beginning of multiplication instruction. Skill at multiplication 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 five months later. Increased multiplication proficiency reflected the operation of the other three types of change. There were large changes in the frequency with which the three approaches were used; use of retrieval increased, whereas use of the other two strategies decreased. 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. Without recognition of the variability of children's strategies, such a differentiated analysis of cognitive growth would have been impossible.

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, Fischer & Patzelt, 2002), for progressively shifting strategy choice toward the more effective approaches (Siegler & Shrager, 1984), and for indicating how gesture-speech mismatch contributes to cognitive growth (Goldin-Meadow & Alibali, 2002).

One lesson from these mechanistic analyses of variability is the importance of conceptual constraints on learning. Contrary to the emphasis of earlier learning theories on blind trial and error, more recent analyses indicate that children's learning in meaningful domains shows remarkably little trial and error (e.g. Siegler & Jenkins, 1989). Thus, even untutored 1- and 2-year-olds do not choose randomly among tools when they start to use them; they choose 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). Such findings suggest the existence of mechanisms that constrain children's approaches to ones that are conceptually plausible.

Another domain in which such constraints appear to operate is basic addition. Siegler and Jenkins (1989) 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 procedures for combining the two addends into a single answer.

This hypothesis motivated Siegler and Crowley (1994) to test whether children possess such a goal sketch before they discover the min strategy. They asked 5-year-olds who did not yet use the min strategy to judge the attractiveness of three addition procedures that a puppet executed: the sum strategy (counting from one), which all of the children already used in their own problem solving; the min strategy (counting from the larger addend), which they did not use; and counting the first addend twice, which they also did not use. 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 sum strategy, which they all already used. 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 allowed mechanistic specification of conceptual constraints on strategy discovery within a computer simulation of discovery of the min strategy (Shrager & Siegler, 1998). Within this model, using strategies to solve problems yields information about the answers to the problems and about the speeds and accuracies characteristic of the strategies and the problems. The model learns which strategies are more effective in general, which work best on problems with specific features, and which work best on particular problems. Each problem-solving effort also yields a trace of the process performed on that trial. As problem-solving becomes increasingly automated, working memory resources are freed, which allows discovery heuristics to examine these traces of problem-solving to see if more efficient processing is possible. If so, the model proposes a new, potentially more efficient strategy, and compares it to goal.
Developmental differences in 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), decrease (Spencer, Verweijen, Diederich & Thelen, 2000), increase and then decrease (Gershkoff-Stowe & Smith, 1997), or stay constant (Frye et al., 2004).

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 been suggested by Goldin-Meadow, Alibali and Church (1993), Thelen (1994), and others.

One source of support for the view that variability tends to wax and wane is a cyclical fashion comes from studies of problem-solving. On balance scale, shadows, projection, false belief, matrix completion, and other problem-solving tasks, performance seems to progress from reliance on a single, systematically wrong approach to a variable state of oscillation among a variety of strategies to consistent use of a more advanced approach (Frye et al., 2004; Steiger & Chem, 1998; Siegel & Svetina, 2002). For example, Hosenfeld, van der Maas and van den Boom (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.

Additional 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 the right hand, sometimes reaching with the left hand) for a prolonged period before eventually returning to consistent right-hand-reach ing (Spencer et al., 2000). 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 repeatedly, kicking both legs simultaneously, or kicking between right and left leg kicks) (Spencer et al., 2000).

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 produce the same type of incorrect strategy in speech and gesture tend to progress to a more variable state, in which their gestures reflect a correct strategy and their speech does not. In contrast, children who are given the same relevant experience but who begin in a variable state, in which their gestures but not their speech express a correct strategy, usually progress to a less variable state, in which gesture and speech express the same correct strategy (Alibali & Goldin-Meadow, 1993). Thus, the disparate observations of age trends in variability seem due to the observations targeting different phases of cyclical increases and decreases in variability.

Theoretical implications and questions

One implication of research on within-child variability is that typical cross-sectional and long-term longitudinal 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 misses short-term regressions and periods of high variability. In a clever recent demonstration of this phenomenon, Adolph, Robson, Young and Gill-Alvarez (submitted for publication) simulated varying sampling intervals by systematically removing observations from a high-density (daily) sampling of infant motor activities. They found that the wider the sampling interval, the more discontinuous and stage-like development appeared. Even sampling intervals that would be considered heroic in usual contexts (e.g. monthly sampling) greatly exaggerated the degree of discontinuity that was evident in daily sampling.

Another intriguing theoretical issue concerns why within-child variability tends to be positively related to subsequent learning. Several explanations have been advanced. Dynamic systems theory postulates that for a system to change, it must first become unstable (Hosenfeld et al., 1997). Variability in the behavior of interest is one sign of such instability. Another hypothesis is that


