Journal of Experimental Psychology:
Human Perception and Performance
1993, Vol. 19, No. 1, 92–107

0096-1523/93/$3.00

Transitions in Learning: Evidence for Simultaneously Activated Strategies

Susan Goldin-Meadow, Howard Nusbaum, Philip Garber, and R. Breckinridge Church

Children in transition with respect to a concept, when asked to explain that concept, often convey one strategy in speech and a different one in gesture. Are both strategies activated when that child solves problems instantiating the concept? While solving a math task, discordant children (who produced different strategies in gesture and speech on a pretest) and concordant children (who produced a single strategy) were given a word recall task. All of the children solved the math task incorrectly. However, if discordant children are activating two strategies to arrive at these incorrect solutions, they should expend more effort on this task than concordant children, and consequently have less capacity left over for word-recall and perform less well on it. This prediction was confirmed, suggesting that the transitional state is characterized by dual representations, both of which are activated when attempting to explain or solve a problem.

Understanding learning has long been one of the primary goals of cognitive psychology. Concept learning, skill acquisition, tacit learning, and perceptual learning have all been studied by examining performance on a variety of tasks before and after some experience. In the broadest terms, theories of learning have been classified as using either accumulation or replacement mechanisms (Mazur & Hastie, 1978). Accumulation theories view learning as the systematic acquisition of increasing amounts of information or skill, whereas replacement theories operate by qualitative reorganizations or changes in mental representations and strategies. Although these different approaches predict relatively subtle differences in the shapes of learning curves (Mazur & Hastie, 1978; Newell & Rosenbloom, 1981; Stigler, Nusbaum, & Chalip, 1988), these two mechanisms should lead to extremely different sequences of specific representations and strategies induced throughout learning (cf. Brown & Carr, 1989; Logan, 1988). Thus, to understand learning, it would seem important to understand the qualitative changes that take place during transitions in learning rather than simply examining levels of performance before, after, and/or during learning.

The transition from novice to expert has been characterized often as a shift from following explicit strategies to more intuitive pattern recognition (see Glaser & Chi, 1988). For example, chess novices apply strategies sequentially to determine the next move, whereas experts seem to recognize directly what the next move should be given a particular board configuration (Chase & Simon, 1973). Further, novices seem to remember novel situations piecemeal, demanding a great deal of working memory, whereas experts chunk familiar situations into meaningful patterns that reduce the demands on working memory (Chase & Ericsson, 1981). Thus, experts do not appear to have better overall memory than novices; rather their memory performance reflects the application of their specific expertise in a particular domain. However, while much research has sought to characterize the state of the novice (i.e., strategy follower) in contrast to that of the expert (i.e., pattern recognizer), this research does not really examine the nature of the cognitive path between these states. In fact, this is a problem in a number of studies that examine learning: Performance, strategies, and mental representations are described before and after learning, without examining in close detail the nature of the changes that occur throughout the period of transition between these states (see Glaser & Bassok, 1989, for discussion of this issue).

Similarly, in research on skill acquisition, a contrast is drawn between the slow, effortful, and controlled performance of the unpracticed subject and the rapid, effortless, and automatized performance of the skilled subject (e.g., Bryan & Harter, 1899; Logan, 1985; Shiffrin & Schneider, 1977). In these studies, emphasis is placed on explaining the transition in processing efficiency that results from skill acquisition, by characterizing the differences between the endpoints of learning. For example, there are proposals that skill acquisition may be explained by compilation of declarative knowledge into procedural form (Anderson, 1982, 1987; Cheng, 1985), increases in associative strength among nodes in memory (Shiffrin & Schneider, 1977), or a shift from algorithmic computation to memory retrieval (Logan, 1988). Morever, all of these explanations assume that the learner has already acquired the relevant knowledge for performing the skilled behavior correctly; the only changes that occur are in the efficiency with which this correct knowledge is used.[1]

Susan Goldin-Meadow, Howard Nusbaum, Philip Garber, and R. Breckinridge Church, Department of Psychology, University of Chicago.

This research was supported by Grant R01 HD18617 from the National Institute of Child Health and Human Development to Susan Goldin-Meadow, and by funds from the Smart Foundation.

We thank Miriam Bassok, Janellen Huttenlocher, Susan Levine, William Meadow, and Jim Stigler for insightful comments in discussions of the work and the manuscript, Esther Thelen and two anonymous reviewers for comments on an earlier draft, and Martha Wagner Alibali and Jill Morford for their help in designing and conceptualizing the study.

Correspondence concerning this article should be addressed to Susan Goldin-Meadow, University of Chicago, Department of Psychology, Chicago, Illinois 60637.

[1] However, see Anderson (1982, 1987), whose model does attempt to take account of an initial period in which correct knowledge is lacking and must be developed. Anderson's model explicitly considers an initial stage of skill acquisition in which general-

Comparable to this work on learning in adults, research in developmental psychology also acknowledges the importance of understanding the transitional period in principle (e.g., Flavell, 1984) but, in practice, often falls short of exploring the period of transition itself. Most developmental studies document the fact that children progress from one state to another but pay little attention to the changes in cognitive processing that take place during the transition between states. For example, one of Piaget's major contributions to the study of children's acquisition of concepts has been the demonstration that a child's understanding of many concepts is, throughout the period of acquisition, systematic and rule-governed. In studies of over a dozen Piagetian problems, Siegler (1981, 1983) has shown that although the particular rules or strategies that children use to solve a task change substantially with age, the percentage of children classified as using a single rule or strategy on that task is high and changes little from ages 5 to 17. Findings of this sort suggest that the acquisition of certain concepts is best characterized as a progression from one (presumably inadequate) rule or strategy to another (more adequate) rule or strategy. Nevertheless, little work has been done designed to explore how children make the transition from one rule-governed state to the next (see, however, Siegler & Jenkins, 1989). Thus, with respect both to children and adults, the study of skill acquisition could benefit from a greater focus on the mechanisms by which new strategies supplant old ones.

The purpose of the present study is to probe the cognitive processes that characterize the transitional state, in particular, the transition from an incorrect, yet rule-governed, understanding of a problem to a correct, rule-governed understanding of the problem. We have chosen to explore this phenomenon in children primarily because, in contrast to adults, it is relatively easy to find a domain where a child is not just inefficient at a task but has an incorrect understanding of the task. We begin by reviewing the relevant work on transitions in children; we consider the implications of our findings for theories of change in adults (particularly theories of skill acquisition) in the discussion.

Transition in the Acquisition of Concepts: The Role of Multiple Strategies

Although it is possible that children (or any learner, for that matter) abruptly and completely abandon one strategy in favor of another when acquiring a concept, it is more likely that a child will continue to entertain an old strategy while beginning to develop a new one. One might therefore expect a period of transition in the acquisition of a concept during which there will be evidence for more than one strategy—an old and a new strategy—in the child's behavior (cf. Siegler & Jenkins, 1989). Thus, there is intuitive reason to believe that, as children acquire a concept, they pass through a transitional period during which they entertain more than one strategy with respect to that concept.

Moreover, there is theoretical reason to believe that it is the simultaneous consideration of more than one strategy that leads to uncertainty which then provides the impetus for transition in the acquisition of concepts. For example, Acredolo, O'Connor, and Horrobin (1989) suggest that it is uncertainty which serves as the primary force underlying cognitive growth, and that this uncertainty stems from the confusion children experience when they consider more than one strategy on a single problem. Similarly, any theory that posits internal conflict as a mechanism of developmental change (cf. Piaget's equilibration theory, 1975/1985) assumes that the impetus for transition comes from discrepancies in the rules or strategies a child uses to solve a problem; in order for these discrepancies to have an impact on the child's development, that child must have at some point considered and compared (albeit probably not consciously) the strategies he has available. For example, within the Piagetian tradition, Langer (1969), Snyder and Feldman (1977) and Strauss (1972; Strauss & Rimalt, 1974) have argued that a child in transition is one who displays at least two functional structures with respect to a concept; the child's appreciation of the discrepancy between those functional structures leads to disequilibrium which then acts as an impetus for change (see Turiel, 1969, 1974, for similar arguments within the domain of moral development).

Even traditions that are distinctly non-Piagetian have proposed that multiple solutions to a single problem provide the motivating force for transition. For example, in his list of a structure-dependent transition mechanisms, Keil (1984) includes resolution of internal inconsistencies or contradictions as a mechanism of change; in order to be internally inconsistent, the child must, at some level, entertain two (incompatible) views of the same problem. In his theory of cognitive development, called skill theory, Fischer (1980) describes five strategies that specify how a skill is transformed into a new, more advanced skill; each of these strategies involves transforming two or more skills with given structures into one or more skills with a new type of structure and thus calls for activation of at least two skills in order for developmental change to occur. From an information processing perspective, Klahr (1984) lists conflict-resolution strategies—strategies that apply when two productions are eligible to be activated on a single problem—as an important mechanism of change in self-modifying systems.

These theoretical considerations lead us to suggest that what characterizes the transitional state is, not just the availability of more than one strategy, but the simultaneous activation and evaluation of those strategies. Is there, in fact, empirical evidence that children who are in transition with respect to a concept simultaneously consider more than one strategy when solving problems instantiating that concept? A number of studies have shown that children who are ready to acquire a concept (and thus can be considered in transition with respect to that concept) vacillate in their responses to a series of problems probing the concept, typically producing one strategy on one problem and a different strategy

---

purpose problem solving strategies are applied to declarative problem information in order to generate (hopefully appropriate) specific solution strategies; these specific strategies, once developed, are then compiled and proceduralized.

on a second problem. For example, a child who is in a period of relatively rapid development with respect to moral reasoning typically produces a large number of responses reflecting reasoning at several different levels on the questions and probes in Kohlberg's moral judgment interview (Turiel, 1969; Walker & Taylor, 1991). This same phenomenon has been observed with respect to a variety of cognitive domains, for example, classification of objects (Kuhn, 1972), map drawing (Snyder & Feldman, 1977), and conservation of area (Strauss & Rimalt, 1974).

The fact that a child vacillates between two different strategies, producing one on one problem and another on a second problem, provides evidence that both strategies are available to the child. However, such vacillations across problems do not provide evidence that the child entertains those strategies simultaneously on the same problem. For example, consider a child who is in the process of acquiring conservation of liquid quantity and who bases her nonconservation reasoning on a height strategy for certain problems and a width strategy for others. Although it is possible that this child activates both strategies on the same problem (and thus may be in state of uncertainty on each problem), this need not be so. The child might, for example, use the height strategy (judging the amount to be more in the tall glass and citing the heights of the glass and the dish as the reason) when the height to width ratio of the glass is above a certain number, but use the width strategy (judging the amount to be more in the wide dish and citing the widths of the glass and the dish as the reason) when the height to width ratio of the glass is below that number. The child thus reasons on the basis of two different strategies—a height strategy and a width strategy—but experiences no uncertainty in deciding which strategy to use on a given problem. It is only when there is evidence that the child has considered both the height and width strategies at the same time on a single problem, and then responds on the basis of just one of those strategies, that we can be confident the child experiences uncertainty.

In order to provide evidence for the hypothesis that it is the simultaneous consideration of multiple strategies that characterizes children in transition, we must show, at a minimum, that the child considers more than one strategy on the *same* problem. As Acredolo and his colleagues (Acredolo & O'Connor, 1991; Acredolo, O'Connor, & Horrobin, 1989) have pointed out, evidence of this sort is difficult to obtain simply because the procedures typically used to tap children's knowledge of a concept encourage the child's natural inclination to close on one solution (see also Miller, Brownell, & Zukier, 1977). In a study designed to overcome this difficulty, Acredolo et al. (1989) provided children with the opportunity to assign probabilities to a variety of alternative solutions to a problem. Using this paradigm, Acredolo et al. found that children (particularly children who had not yet acquired conservation according to traditional measures) frequently did consider more than one solution to be possible on a single conservation problem. Acredolo's findings show that children can consider more than one strategy on a single problem when given a variety of strategies or solutions to choose from. However, it is important to note that data of this sort do not (and, indeed, cannot) demonstrate that a child spontaneously entertains more than one strategy in solving a problem.

Children rarely cite more than one strategy when asked to explain how they solved a particular problem; thus, their verbal explanations will not necessarily reveal whether they have considered multiple strategies on a single problem. However, previous work has shown that, when asked to explain their performance on a task, children frequently gesture along with their spoken explanations, and these gestures often convey substantive information about the task itself (e.g., Evans & Rubin, 1979). Our previous work has shown that, while gesture may convey the same information as conveyed in speech (and thus match speech), this is not always the case. At times, a child's gestures will convey a different strategy from the one conveyed in the speech that accompanies those gestures, thus suggesting that the child has, at least at some level, simultaneously considered more than one strategy on a single problem. We have found this phenomenon of gesture-speech mismatch in studies of the acquisition of two different concepts at two different ages: conservation in 5- to 8-year-olds (Church & Goldin-Meadow, 1986) and mathematical equivalence in 9- to 10-year-olds (Perry, Church, & Goldin-Meadow, 1988). In the next section, we review our findings on gesture-speech mismatch in the acquisition of mathematical equivalence and consider the implications of those findings for understanding transition in the acquisition of concepts.

More Than One Strategy in a Single Explanation: Gesture–Speech Mismatch

Perry et al. (1988) tested children between the ages of 9 and 10 on their understanding of equivalence in addition problems (i.e., the understanding that one side of an equation represents the same quantity as the other side of the equation). Children were asked to solve six problems of the form $5 + 3 + 4 = \_\_\_ + 4$ and to explain each of their solutions. When asked to explain their solutions, the children usually gestured spontaneously while speaking and often used those gestures to convey specific strategies that described how to solve the problem. At times, the strategy conveyed in gesture matched the strategy conveyed in the speech accompanying that gesture. For example, one child indicated that he had added all of the numbers in the problem to get the answer, both in speech ("I added 5 plus 3 plus 4 plus 4 equals 16") and in gesture (the child pointed at the 5, pointed at the 3, pointed at the left 4, pointed at the right 4, and then pointed at the blank).

However, as mentioned above, at other times, the gestures produced by the children did *not* convey the same strategy as the speech which accompanied that gesture. For example, one child, in speech, indicated that he had added the numbers on the left side of the equation to get the answer ("I added 5 plus 3 plus 4") but, in gesture, indicated that he had considered all of the numbers in the problem (he pointed at the 5, the 3, the left 4, the right 4, and then the blank).

Perry et al. (1988) found that the children in their study varied in the number of gesture–speech mismatches they produced, some producing none and some producing as many as 6 (out of 6). Thus, some children routinely produced one strategy in their spoken responses and a different strategy in the accompanying gesture, suggesting that they not only had two strategies in their repertoire but that they also considered those strategies simultaneously while explaining a single problem.

Important to our exploration of the role that multiple strategies play in transition is the fact that Perry et al. (1988) found that the children who produced many gesture–speech mismatches in their explanations (labeled *discordant* children by Perry et al.) were more likely to benefit from instruction in equivalence than the children who produced few gesture-speech mismatches (labeled *concordant* children). The relative ease with which the discordant children learned the concept was particularly striking given that none of the children (concordant or discordant) was correct on any of the problems before training. Moreover, the explanations produced by all but one of the children (a discordant child) before training, contained strategies which, if followed, led to incorrect solutions. Thus, the discordant children—who gave explicit evidence of considering two (incorrect) strategies on a single problem—were in transition with respect to acquiring mathematical equivalence, while the concordant children—who gave evidence of considering only a single (incorrect) strategy on a problem—were not (see Church & Goldin-Meadow, 1986, for comparable results with respect to conservation).

Do Children in Transition Activate More Than One Strategy When Solving Problems?

The findings described above suggest that children in transition with respect to a concept do simultaneously consider more than one strategy when explaining their beliefs about the concept. However, the fact that children may exhibit two strategies when explaining how they solved a problem does not necessarily mean that the children consider both strategies when actually solving the problem. Discordance could reflect post hoc reasoning processes rather than on-line problem solving. The goal of the present study was to determine whether discordant children not only consider more than one strategy when they explain their solutions to a problem, but also activate those strategies when they solve the problem itself. We base our study design on the assumption that the simultaneous activation of multiple strategies will also have implications for the deployment and use of cognitive resources such as working memory (Baddeley, 1986).

When individuals are asked to solve problems, recall items, learn concepts, or understand language, conceptual representations under cognitive control are activated (Posner, 1978; Shiffrin, 1976). The operation of these active control processes requires some form of cognitive capacity (e.g., Navon & Gopher, 1979; Shiffrin, 1976) and can be shown to limit the availability of working memory for other cognitive processes (Baddeley, 1986; Logan, 1979). Nusbaum and Schwab (1986) have argued that increased demands on cognitive capacity will occur whenever there are alternative hypotheses or interpretations for any particular cognitive process. For example, in speech perception, one acoustic cue may signal any one of several different phonemes; thus recognition of that cue may require more capacity than recognition of a cue for which only a single interpretation exists. In terms of solving a problem, if more than one strategy or solution is possible, evaluation of the multiple solutions should require more capacity than evaluating a single strategy for a different problem. If multiple strategies are active simultaneously, more working memory will be required than if a single strategy is active.

Thus, we hypothesize that if the child in transition has alternative representations of a particular concept or problem, these multiple representations will demand additional cognitive capacity and should be detectable through the use of an unrelated task that makes demands on this same cognitive resource (cf. Logan, 1979). In effect, compared to a child who activates only a single strategy, a child who activates multiple strategies on one task should be burdened by this increased cognitive load and have less capacity "left over" to simultaneously perform a second (unrelated) task.

The present study tests the specific prediction that children who produce two different strategies when explaining their solutions after solving a task (one in gesture and one in speech, i.e., discordant children) activate both of those strategies and thus expend more effort when actually solving the task, compared to children who produce one strategy in their explanations (either in speech alone or in both gesture and speech, i.e., concordant children). To test this prediction, we first identified children as concordant or discordant with respect to mathematical equivalence based on their explanations on a pretest. We next compared the concordant and discordant children's performance on a primary task (mathematical equivalence) and on a simultaneously performed secondary task (word recall). We hypothesize that the primary math task demands cognitive capacity in the form of working memory, and that performance on the word recall task (which also makes demands on working memory) reflects the residual availability of this resource (see Brown, McDonald, Brown, & Carr, 1988; Logan, 1979). If discordant children activate multiple strategies while solving the math problems and consequently expend more effort than concordant children on this primary task, they ought to have less capacity left over for, and therefore perform less well on, the secondary word recall task.

Method

Subjects

Seventeen 4th-grade students (7 girls and 10 boys) from a parochial elementary school in Chicago participated in the study. Three children who were successful on three or more of the six addition problems on a pretest (see below) were eliminated from the study. These children were eliminated because our goal was to explore children who had not yet acquired mathematical equivalence. The remaining 17 children comprised the subjects for the study and ranged in age from 9 years, 4 months to 10 years, 6 months (M = 10 years).

Pretest

Each child was given a paper-and-pencil test containing six addition problems, three of the form 6 + 3 + 8 = ____ + 8 and three of the form 3 + 7 + 5 = 3 + ____. Upon completion of the problems, the child accompanied the examiner to a chalkboard. The examiner then wrote the first problem of the pretest, along with the child's answer, on the board and asked the child to explain how he or she had solved the problem. This procedure was repeated for each of the six problems. The pretest, as well as the rest of the session, was videotaped.

Primary Task: Math Problems

In the primary task, each child was asked to solve (but not explain) 24 addition problems of two types: (a) Twelve Easy problems of the form 4 + 7 + 3 + 5 = ____. Note that there were no numbers on the right side of the equation in these problems. Fourth-grade children typically solve problems of this type without error, and we therefore expected all of the children to activate a single (correct) strategy when solving the Easy problems.[2] (b) Twelve Hard problems of the form 3 + 6 + 7 = ____ + 8, or 5 + 9 + 4 = 3 + ____. These problems were identical to those used on the pretest except that the number on the right side of the equation did not duplicate any of the numbers on the left side of the equation; this change was made so that there would be four different numbers in both the Hard and the Easy problems (in order to minimize adding errors, the numbers used in both the Easy and Hard math problems were restricted to single-digit numbers between 3 and 9). On the basis of our previous work, we expected concordant children to activate a single strategy when solving Hard problems and discordant children to activate multiple strategies.

Secondary Task: Word Recall

Before they were asked to solve each math problem, the child was given a list of words and told that he or she would be asked to recall the words after solving the problem. For each problem, the experimenter read the word list to the child, wrote the math problem on the board and asked the child to solve it, and then asked the child to recall the words. Children were asked to recall words rather than numbers in order to make the secondary task distinct from the primary task (which involved adding numbers).

Two types of word lists were used: (a) a 1-word list that was expected to put relatively little strain on the child's capacity and thus was considered a condition of low cognitive load, and (b) a 3-word list that was expected to strain the child's capacity and thus was considered a condition of high cognitive load. The words used were all monosyllabic, concrete nouns culled from the highest frequency words in Kučera and Francis (1982).

Six of the Hard math problems were preceded by a 1-word list, and six were preceded by a 3-word list. The 12 Easy math problems were similarly divided: 6 preceded by a 1-word list and 6 preceded by a 3-word list. The order in which the four sets of six problems were presented was randomized.

Coding Explanations on the Pretest

All verbal and gestural explanations of the problem solutions produced on the pretest were evaluated in terms of the strategy each conveyed. For each subject, verbal and gestural explanations were coded separately by two independent coders. Verbal explanations were coded by listening to the audio portion of the videotape only, without reference to the video portion (i.e., sound with the picture turned off). Gestural explanations were coded by viewing the video portion of the videotape only, without reference to the audio portion (i.e., picture with the sound turned off). Finally, the relationship between gesture and speech was evaluated by comparing the codes for the verbal and gestural components of a given explanation.

Coding types of explanations in speech alone. Each verbal explanation was coded according to the system described in detail in Perry et al. (1988). Like the children in Perry et al.'s studies, the children in this study produced a variety of spoken explanations, some of which described strategies yielding incorrect solutions to the math problems, and some of which described strategies yielding correct solutions. There were two predominant strategies leading to *incorrect* solutions in speech (accounting for 91% of the 101 spoken explanations): add all the numbers in the problem (*Add-All*), and add the numbers which appeared to the left of the equal sign (*Add-to-Equal*).[3] In addition, the children produced a small number of idiosyncratic strategies (accounting for 2% of the spoken explanations) also leading to incorrect solutions (e.g., add the numbers on the left side of the equal sign and divide by the number on the right side of the equal sign; or because the numbers in the problem form a pattern of odd numbers, put the next odd number in the series in the blank).

A small number of spoken strategies leading to correct solutions (accounting for 1% of the spoken explanations) were also produced on the pretest: group the numbers that did not appear on both sides of the equation (*Grouping*), and add the numbers on the left side of the equation and subtract the number on the right (*Add-Subtract*). Finally, the children produced a small number of strategies (accounting for 6% of the explanations) that could not be assigned a strategy and were consequently classified as ambiguous.

Coding types of explanations in gesture alone. Gestures were transcribed by a second coder using the lexicon of gestural strategies for solving these problems established by Perry et al. (1988), in which each of the verbal strategies described above has a counterpart in gesture. As in speech, there were two predominant strategies leading to incorrect solutions in gesture (accounting for 84% of the 85 gestural explanations), *Add-All* and *Add-to-Equal*, as well as a small number of idiosyncratic strategies (accounting for 5% of the explanations) leading to incorrect solutions.

In addition, there were two strategies leading to *correct* solutions in gesture (accounting for 9% of the explanations), *Add-Subtract* and *Equalizer* (make both sides of the equation sum to the same total). Finally, the children produced a small number of strategies (accounting for 2% of the gestural explanations) which could not be assigned a strategy and were consequently classified as ambiguous. Examples of how both gestural and verbal productions were coded appear in Table 1.

Coding the relationship between speech and gesture. In the final stage of coding, the verbal explanation and the gestural explanation given for each problem were compared. If the strategies given in gesture and in speech were identical, the explanation was coded as a gesture-speech match. If the strategies given in

---

[2] In a pilot study of 12 children who had not yet acquired mathematical equivalence, we found that all 12 were, in fact, concordant when they explained Easy problems but that 7 of those 12 were discordant when they explained Hard problems. This means that 7 of the 12 children did not have the same concordance–discordance status on the two types of problems, confirming once again (cf. Perry, Church, & Goldin-Meadow, 1988) that discordance is not a characteristic of the child but rather a characteristic of the cognitive processes activated at the time of explaining a problem (and perhaps of solving it as well).

[3] The total number of explanations was 101 rather than 102 (6 × 17 subjects) because the sixth response from 1 child (who was discordant) was not captured on videotape.

gesture and in speech were different, the explanation was coded as a gesture-speech mismatch.

For example, in response to the problem, 4 + 7 + 5 = 4 + ____, if a child said, "I added the 4, the 7, and the 5" (Add-to-Equal) while pointing to the left 4, the 7, and the 5 (Add-to-Equal), that response would be coded as a gesture–speech *match* because both gesture and speech conveyed the same strategy. Such a response suggests that the child was, in fact, entertaining only one (incorrect) hypothesis about how to solve the problem.

In contrast, in response to the same problem, if a child said, "I added the 4, the 7, and the 5" (Add-to-Equal) while pointing to the left 4, the 7, the 5, and the right 4 (Add-All), that response would be coded as a gesture–speech *mismatch* because the strategy conveyed in speech was not the strategy conveyed in gesture. Such a response suggests that the child was entertaining two hypotheses about how to solve the problem, both incorrect. Similarly, in response to the same problem, if a child said, "I added the 4, the 7, and the 5" (Add-to-Equal) while first sweeping under the left side of the problem and then sweeping back and forth underneath the right 4 and the solution (Equalizer), that response would be coded as a gesture–speech mismatch and would be considered evidence that the child was entertaining two hypotheses, an incorrect one in speech and a correct one in gesture (see examples in Table 1).

Following Perry et al. (1988), children who produced 3 or more responses across the pretest problems in which the gestured strategy did *not* match the spoken strategy were classified as discordant; children who produced 2 or fewer mismatches or who produced no gestures at all were classified as concordant. Only 2 of the 17 children produced no gestures at all (the remaining 15 children gestured on all but 4 of their 89 explanations). These 2 children were considered concordant because they (like the concordant children who produced gestures) used only one strategy per explanation (see Perry, Church, & Goldin-Meadow, 1992, for discussion of this coding decision). The pattern of responses for concordant children in the figures presented below was the same with or without including the data for these 2 children, lending validity to this decision.

Interrater reliability was established for the coding system by having two trained coders independently transcribe and code videotapes of explanations produced during the pretest. There was 93% agreement between coders on coding strategies in speech alone, 84% agreement on coding strategies in gesture alone, and 92% agreement on coding the relationship between gesture and speech. The few discrepancies between coders were resolved by discussion.

Analysis of the Primary Math Task and the Secondary Word Recall Task

For the primary task, the number of math problems the child solved correctly on each trial was recorded. For the secondary task, the number of words the child recalled correctly on each trial was recorded. The child was given credit for a word list only if the entire list was recalled correctly (if we consider the unit of analysis to be the word rather than the list and count the proportion of words recalled correctly, the pattern of results presented in Figure 3 [see below], although less pronounced, remains the same).

All of the data were analyzed by an analysis of variance with repeated measures, with group (discordant vs. concordant) as the between-subjects factor, and type of math problem (easy vs. hard) and level of cognitive load (1-word low load vs. 3-word high load) as within-subjects factors.

Table 1
Types of Gesture–Speech Explanations

Type of explanation	Gesture	Speech
Gesture–speech match (gesture, speech incorrect)	Point to 3, to 4, to left 5 (Add-to-Equal)	"I added 3 + 4 + 5 and I got 12" (Add-to-Equal)
Gesture–speech mismatch (gesture, speech incorrect)	Point to 3, to 4, to left 5, to right 5 (Add-All)	"I added 3 + 4 + 5 and came up with 12" (Add-to-Equal)
Gesture–speech mismatch (gesture correct, speech incorrect)	Sweep under the left side of the problem, sweep under the right side of the problem (Equalizer)	"I added 3 + 4 + 5 and I got 12" (Add-to-Equal)
Gesture–speech mismatch (gesture incorrect, speech correct)	Point to 3, to 4, to left 5, to right 5 (Add-All)	"I just added 3 + 4 so I put 7" (Grouping)

Note. The math problem eliciting these gesture-speech explanations is: 3 + 4 + 5 = ____ + 5. The brackets contain the name of the strategy that each string of gestures and that each string of words exemplifies. Note that in the mismatch explanations, the strategy conveyed in gesture is not the same as the strategy conveyed in speech. In the first mismatch, the strategy in gesture (Add-All) leads to an incorrect solution and the strategy in speech (Add-to-Equal) leads to a different, but also incorrect solution. In the second mismatch, the strategy in gesture (Equalizer) leads to a correct solution, but the strategy in speech (Add-to-Equal) leads to an incorrect solution. In the third mismatch, the strategy in gesture (Add-All) leads to an incorrect solution, but the strategy in speech (Grouping) leads to a correct solution.

Results

Classification of Concordant Versus Discordant Children on the Basis of the Pretest

On the basis of the six explanations they produced on the pretest, the 17 children were divided into two groups: 11 children, whose number of gesture–speech mismatches ranged from 0 to 1 ($M = 0.64$), were classified as a concordant (7 boys and 4 girls), and 6 children, whose number of gesture–speech mismatches ranged from 3 to 4 ($M = 3.2$), were classified as discordant (3 boys and 3 girls). The concordant children ranged in age from 9 years, 9 months to 10 years, 3 months (M = 10 years), and the discordant children ranged in age from 9 years, 4 months to 10 years, 6 months (M = 10 years).

Types of Explanations Produced on the Pretest

Explanations in speech. The two groups of children did not differ in the types of strategies they produced in speech. The mean number (out of 6) of spoken strategies leading to incorrect solutions was 5.77 ($SD = .61$) for the concordant children and 5.00 ($SD = .95$) for the discordant children, $t(15) = 2.062$, $p = .06$. None of the concordant children and only 1 discordant child produced strategies leading to correct solutions in speech. Finally, the mean number of ambiguous responses in speech was low and did not differ in the two groups: .23 ($SD = .61$) for the concordant children versus .58 ($SD = .80$) for the discordant children, $t(15) = 1.035$, $p = .32$.

Explanations in gesture. As described above, 2 children did not gesture on any of their explanations and, because their responses contained only one strategy per explanation, were classified as concordant. Eliminating these 2 children from the analysis of gestural responses, we found that concordant and discordant children differed somewhat in the explanations they produced in gesture. The mean number of gestural strategies leading to incorrect solutions was significantly higher for the concordant children (5.44, $SD = .88$) than for the discordant children (4.45, $SD = .81$), $t(13) = 2.22$, $p = .045$. Moreover, the mean number of gestural strategies leading to correct solutions was significantly higher for the discordant children (1.06, $SD = .65$) than for the concordant children (.11, $SD = .33$), $t(13) = 3.471$, $p = .002$. As was the case for speech, the two groups of children did not differ in the mean number of ambiguous responses they produced in gesture (.11, $SD = .33$, for the concordant children vs. .17, $SD = .41$, for the discordant children), $t(13) = 0.29$, $p = .78$. Finally, the mean number of responses given that did not contain gesture was low and did not differ for the two groups (.33, $SD = .71$, for the concordant children vs. .17, $SD = .41$, for the discordant children), $t(13) = 0.519$, $p = .61$.

Types of gesture–speech mismatches. By definition, the concordant children produced few gesture–speech mismatches on the pretest. Five of the 7 mismatches they did produce contained two strategies that both led to incorrect solutions. One mismatch contained an incorrect strategy in speech but a correct strategy in gesture. Finally, 1 child produced a mismatch in which the strategy conveyed in speech was ambiguous, but was different from the ambiguous strategy conveyed in gesture.

The discordant children produced 19 gesture–speech mismatches, 9 of which contained two incorrect strategies. Seven mismatches (produced by 5 different children) contained an incorrect strategy in speech but a correct strategy in gesture. The remaining two mismatches (both produced by the same child) contained a correct strategy in speech and an incorrect strategy in gesture. Finally, 1 child produced a mismatch which contained two different ambiguous strategies.

Match between explanations and solutions on the pretest. Recall that children were included in the study only if the majority of their solutions to the six pretest addition problems were incorrect. In fact, all 11 of the concordant children and 6 of the 7 discordant children produced no correct solutions on the pretest at all. However, for both groups, the solutions the children produced, although incorrect, tended to reflect coherent strategies. For example, a child who gave 17 as the solution to the problem 4 + 3 + 5 = ____ + 5 appeared to have used an Add-All strategy to arrive at his solution; in contrast, a child giving 12 as the solution appeared to have used an Add-to-Equal strategy. All but 2 of the 102 solutions produced by the children were generated by recognizable strategies (one was produced by a concordant child and the other by a discordant child), and Add-All or Add-to-Equal accounted for 96% of those recognizable strategies.

We next asked whether the strategy a child used in solving a particular problem was consistent with the strategy expressed in his or her explanation of that problem. Overall, we found that 90% of the children's solutions were generated by strategies that could be found in the explanation for that solution; that is, the children were relatively accurate in their explanations of what they did. Moreover, we found that the concordant and discordant children did not differ in accuracy—both groups tended to mention the strategy they actually used to solve the problem in speech alone, or in both gesture and speech. The mean number of solutions that were accurately described in speech (but not in gesture) in the accompanying explanation was 1.91 ($SD = 2.26$) for the concordant children versus 2.00 ($SD = .89$) for the discordant children, $t(15) = 0.094$, $p = .93$. The mean number of solutions that were accurately described in speech and also in gesture in the accompanying explanation was 3.82 ($SD = 2.14$) for the concordant children versus 2.50 ($SD = .55$) for the discordant children, $t(15) = 1.465$, $p = .16$. Only 1 child (who was discordant) produced one solution that was not captured in the child's spoken explanation but did appear in the child's gestural explanation.

The mean number of solutions that were not described in either speech or gesture in an explanation was .27 ($SD = .65$) for the concordant children versus 1.17 ($SD = 1.17$) for the discordant children, $t(15) = 2.055$, $p = .06$. It is worth noting that many of the solutions that could not be found in the particular explanation generated for that solution were, in fact, traceable to other explanations in the child's repertoire (2 of the concordant children's 3 responses of this type were found somewhere in the child's repertoire, as were 4 of the discordant children's 7 responses of this type). In other words, the strategy reflected in the child's solution was one that the child was able to articulate, albeit not always in response to that particular question.

In sum, there was a very good match between the children's solutions and the strategies expressed in their explanations. Further, for both concordant and discordant children, speech appeared to have a privileged position within the explanation, more accurately reflecting the strategy the child actually used in generating a solution to the problem. (Indeed, the only child who produced any correct solutions on the pretest was the 1 child found to produce correct strategies in speech in his explanations on the pretest; this child was discordant.) Gesture, when it differs from speech, thus appears to reflect implicit strategies in the child's repertoire—strategies that are not actually used to generate the solution to the problem but, as we will show below, which do appear to have an impact on the amount of effort the child expends in solving the problem.

Number of Strategies Per Explanation on the Pretest

We have hypothesized that the discordant children will activate two strategies on a single problem when solving problems on the primary math task. We based this hypothesis on the fact that in previous work, discordant children have been shown to produce two different strategies, one in speech and one in gesture, in their explanations of a single problem (cf. Church & Goldin-Meadow, 1986; Perry et al., 1988). Our first step here is to explore how frequently the discordant children in this sample produced two different strategies on a single problem in their explanations of that problem.

To address this issue, we classified the explanations the children produced according to the number of strategies per explanation: 1-strategy responses (those that contained one strategy in speech and no gesture, or the same strategy in both gesture and speech) and 2-strategy responses (those that contained at least two different strategies, one in speech and a different one in gesture). Figure 1 presents the mean number of 1-strategy and 2-strategy responses produced by the concordant and discordant children. As expected given the definition of discordance, the concordant children produced significantly more 1-strategy responses than the discordant children: 5.36 (SD = .67) versus 2.67 (SD = .52), $t(15) = 8.488$, $p < .001$. Moreover, the discordant children produced significantly more 2-strategy responses than the concordant children: 2.83 (SD = .75) versus 0.45 (SD = .52), $t(15) = 7.698$, $p < .001$. Indeed, all 6 of the discordant children produced at least two 2-strategy responses, whereas none of the 11 concordant children did. Thus, the discordant children did indeed produce 2-strategy responses, and did so more often and more consistently than the concordant children.

In addition, the children in both groups produced only a small number of responses that contained no recognizable strategies: 2 responses in which speech was ambiguous and there was no gesture (1 produced by a concordant child and 1 by a discordant child), and 2 responses in which both gesture and speech were ambiguous (1 produced by a concordant child and 1 by a discordant child).

Performance on the Math Problems (the Primary Task)

We turn next to the children's performance when asked to solve (but not to explain) the math problems on the primary task. Figure 2 presents the proportion of Easy and Hard math problems solved correctly by concordant and discordant children under conditions of low (1-word list) and high (3-word list) cognitive load. As predicted, concordant and discordant children performed alike on the primary task: They were correct on the Easy math problems and incorrect

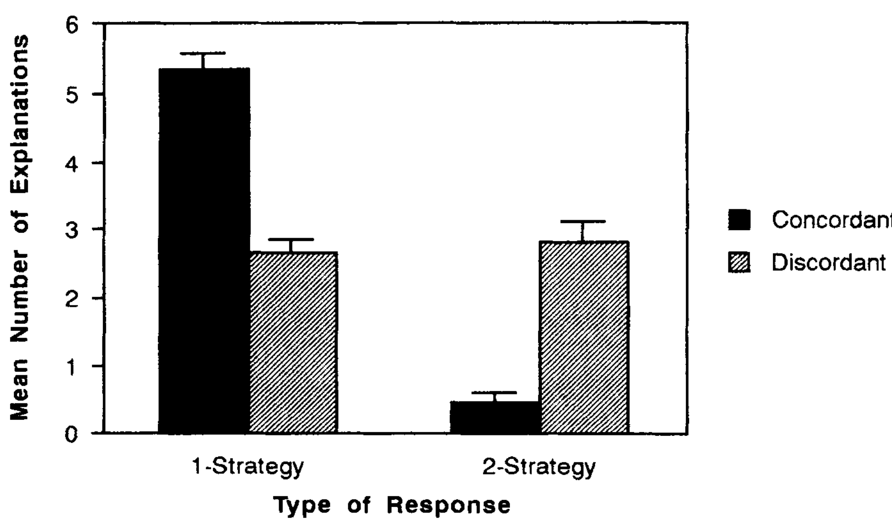

Figure 1. Number of strategies per explanation produced on the pretest. (The mean number of 1-strategy versus 2-strategy explanations produced by the concordant and discordant children on the pretest.)

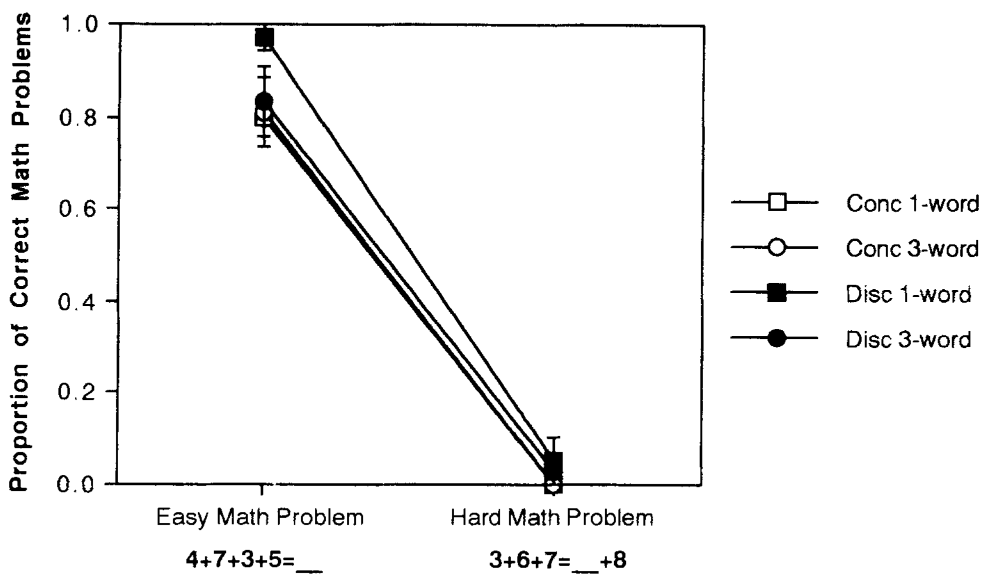

Figure 2. Performance on the math problems (the primary task). (The proportion of Easy and Hard math problems solved correctly by concordant and discordant children under conditions of low [1-word list] and high [3-word list] cognitive load.)

on the Hard math problems. Performance on the Easy problems was significantly higher than on the Hard problems, $F(1, 15) = 360.18$, $p < .001$, and there was no effect of concordant versus discordant status, $F(1, 15) = 2.29$, $p = .15$, or of low versus high cognitive load, $F(1, 15) = 2.81$, $p = .11$.

Thus, there was no difference between the discordant and concordant children in their performance on the math problems—they both succeeded on the Easy problems and failed on the Hard problems. However, on the basis of their pretest explanations, we hypothesized that the discordant children (and not the concordant children) were activating multiple strategies when they solved the Hard problems, and thus were working harder to arrive at their incorrect solutions than the concordant children. To test this hypothesis, we look next at performance on the word recall task (which we assume uses the same working memory as the math task) in order to gauge how much effort the children expended on the math task.

Performance on the Word Lists (the Secondary Task)

Figure 3 presents the proportion of word lists accompanying Easy and Hard math problems that were recalled correctly by concordant and discordant children under conditions of low (1-word list) and high (3-word list) cognitive load. Looking first at main effects, we found an overall effect of list length on recall; that is, performance on the 1-word list was significantly better than on the 3-word lists, $F(1, 15) = 38.297$, $p < .0001$. There was no overall effect of concordant versus discordant status, $F(1, 15) = 3.206$, $p = .09$, or of easy versus hard math problems, $F(1, 15) = 2.090$, $p = .17$. However, as predicted, there was an interaction between list length, concordant versus discordant status, and easy versus hard math problems, $F(1, 15) = 5.929$, $p = .03$.

We turn next to planned comparisons between the groups. Again, as predicted, there was no difference between the concordant and discordant children on the proportion of word lists recalled correctly when solving the Easy math problems (i.e., the problems on which all children were expected to activate only one strategy): Both groups remembered the same smaller proportion of the 3-word lists than the 1-word lists when solving the Easy math problems, $F(1, 15) = 0.048$, $p = .83$.

The concordant children were also expected to activate only one strategy when solving the Hard math problems. Consequently, their performance on the word lists was predicted to be the same for the Easy and Hard math problems, and it was for both the short and long word lists, $F(1, 15) = 0.139$, $p = .71$.

In contrast, the discordant children were expected to activate multiple strategies when solving the Hard math problems. Consequently, the discordant children were predicted to do less well on the secondary task when that task strained cognitive capacity, that is, on the high cognitive load trials. Indeed, under conditions of high cognitive load (i.e., when asked to recall the 3-word lists), the discordant children performed significantly less well on the word lists accompanying the Hard math problems (on which they were expected to activate two strategies) than did the concordant children (who were expected to activate only one strategy, $F(1, 15) = 16.477$, $p = .001$.

Are the Discordant Children More Confused Than the Concordant Children?

The discordant children were found to perform less well than the concordant children on the 3-word lists accompanying the Hard math problems. We have argued that they

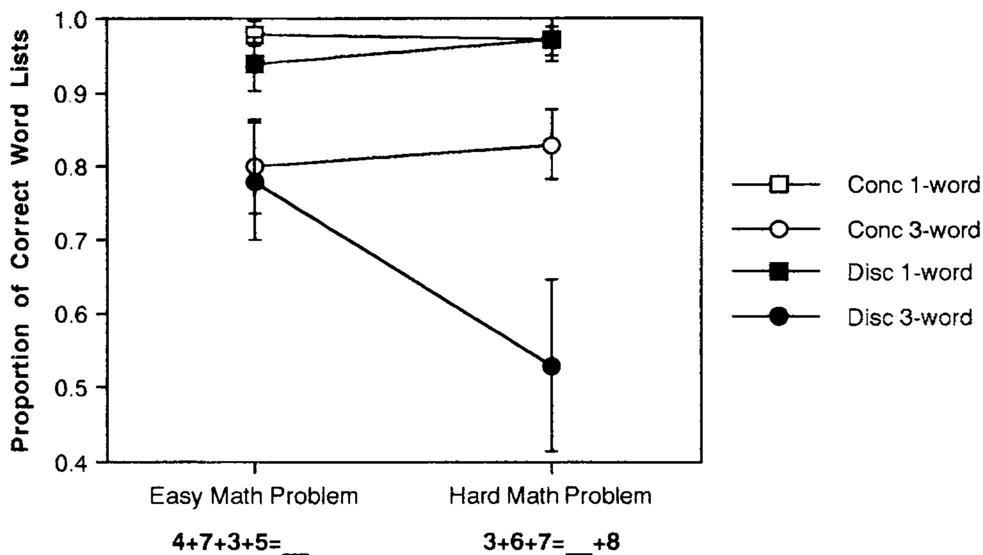

Figure 3. Performance on the word lists (the secondary task). (The proportion of word lists preceding Easy and Hard math problems that were recalled correctly by concordant and discordant children under conditions of low [1-word list] and high [3-word list] cognitive load.)

did so because they activated two strategies when solving the Hard problems, whereas the concordant children activated only one. However, one might offer an alternative explanation—that the discordant children performed less well because they were more confused about how to solve the Hard math problems than the concordant children. Neither group of children produced correct solutions on the Hard problems (see Figure 2); however, this floor effect might obscure potential differences in the abilities of the discordant and concordant groups, differences that could account for the discordant children's relatively poor performance on the 3-word lists that accompanied the Hard math problems.

In a sense, the fact that the discordant children did so poorly on the 3-word lists accompanying the Hard problems in and of itself argues that these children were in a state of confusion. The central issue, however, is what causes this confusion. On one hand, confusion might be caused by some characteristic of the children such as a general lack of ability. For example, given the fact that there are individual differences in working memory capacity (cf. Hasher & Zacks, 1979), one might argue that the discordant children performed less well on the word lists accompanying the Hard problems because they had less capacity than the concordant children. However, it is important to point out that we are not putting forth discordance as a general characteristic of the child, but rather as a characteristic of the cognitive processes activated at the time of solving a problem. We are assuming that the discordant children would not be discordant with respect to all concepts and, in fact, would be concordant if asked to explain their solutions to the Easy problems. Indeed, in a separate study of 12 children who had not yet acquired mathematical equivalence, we found that all 7 of the children who were discordant in their explanations of Hard problems were concordant when they explained Easy problems. Thus, in order to support the individual differences in capacity argument, one would have to argue that the discordant children had less capacity for math problems of this type than the concordant children. This argument is particularly difficult to credit because it is the discordant children—and not the concordant children—who have been found to learn the concept when given instruction in math problems of this type (Perry et al., 1988; see also Church & Goldin-Meadow, 1986, for comparable results with respect to a second concept, conservation).

On the other hand, confusion might reflect a lack of specific knowledge about the task or uncertainty in applying a single strategy to the task. Under this theory, the discordant children might have performed less well because they had less well-formulated strategies overall than the concordant children, or because they were more uncertain of the single strategy that they used on each Hard math problem than the concordant children. We think this possibility unlikely for several reasons. First, when asked to explain their solutions to the Hard math problems on the pretest, the discordant children were no more likely to produce incoherent, unrecognizable strategies than the concordant children. Recall that the two groups of children did not differ in the mean number of ambiguous responses they produced, either in speech or in gesture. Moreover, the two groups produced an equally small number of responses in which there were no recognizable strategies (2 in each group). Indeed, the discordant children produced the same types of strategies as the concordant children in speech and, in fact, produced more correct strategies than the concordant children in gesture. Thus, an analysis of the explanations of the Hard problems suggests that the discordant children were no more confused than the concordant children and, if anything, were somewhat more advanced in their knowledge than the concordant children.

Second, if the discordant children were more confused and generally less competent in solving the Hard math prob-

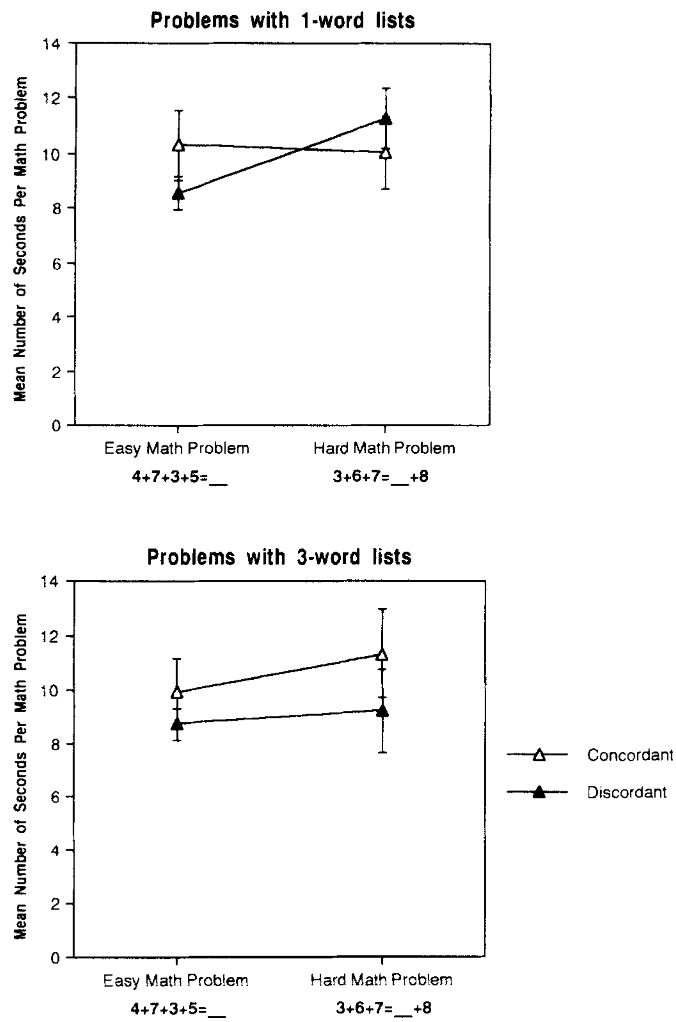

Figure 4. Time taken to solve a math problem on the primary task. (The mean number of seconds per problem the concordant and discordant children took when solving the math problems on the primary task.)

lems than the concordant children, we might expect them to demonstrate this confusion in the length of time taken to solve the Hard problems. To address this question, we calculated the amount of time each child took to provide an answer to each of the 24 problems on the primary math task. Working off of the videotapes, we calculated the time (in hundredths of a second) between when the experimenter finished writing the problem on the board and when the child began writing his or her answer in the blank. Figure 4 presents the mean number of seconds the concordant and discordant children took to provide answers to the Easy and Hard math problems, calculated separately for problems accompanying 1-word versus 3-word lists. Not surprisingly, we found that the children took longer to solve the Hard problems than the Easy problems, $F(1, 15) = 6.643, p = .02$. However, there were no significant differences between the concordant and discordant children, $F(1, 15) = 0.298, p = .59$, no effect of list length, $F(1, 15) = 0.102, p = .75$, and no interactions among any of the factors. Thus, the discordant children did not take more time to solve the math problems than did the concordant children and, in this sense, were no more confused than the concordant children.

Although the discordant children did not seem to be particularly inept on the Hard math problems, it is still possible that the effort they expended on these problems was due, not to the fact that they activated two strategies (as we have hypothesized), but to the fact that they activated one incompletely learned, and therefore inefficiently processed, strategy. Again, we think this possibility unlikely primarily because there is no evidence that the discordant children were any less efficient in processing their single strategies than the concordant children. Both groups of children were expected to activate a single strategy on the Easy problems, and there were no differences between the concordant and discordant children's word recall performance for these problems—even under conditions of cognitive load on the 3-word lists. Moreover, it is likely that the strategies activated on the Easy problems were the same strategies activated on the Hard problems, because the most frequently produced strategies on the Hard problems (Add-All and Add-to-Equal which lead to incorrect solutions on the Hard problems) lead to correct solutions on the Easy problems.[4] Thus, it is difficult to argue that the discordant children had learned their strategies less completely and applied them less efficiently than the concordant children.

In sum, the discordant children performed poorly on the 3-word lists accompanying the Hard math problems. If we ascribe this poor performance to confusion, it is important to acknowledge that the confusion stemmed neither from a general lack of ability, nor from a specific lack of knowledge of the task. Rather, the confusion appears to be best explained by the hypothesis that the discordant children activated, and therefore were forced to grapple with, more than one strategy on a single problem.

Discussion

The Discordant State as a Transitional State

A priori one might argue that children's communications about their understanding of a concept need not reflect in any way what actually goes on when children solve problems instantiating that concept (see Ericsson & Simon, 1980; Nisbett & Wilson, 1977, for discussion of this issue). However, the results of the present study suggest that this is not the case. Our data show that children's explanations of a concept not only indicate whether they are in a transitional state with respect to that concept, but also reflect the way in which they actually solve problems instantiating that concept.

Moreover, the data from this study bear on the question of what it means for an individual to be in a transitional state. The results distinguish between two distinct views of the transitional state: (a) The hypothesis that children in a transitional state with respect to a concept have greater facility with that concept than children who are not in a transitional state. If this hypothesis were correct, the discordant children should have expended less effort on a task tapping this concept and therefore should have had more effort left over, allowing them to perform better on the secondary task than the concordant children; in fact, they performed worse. (b) The hypothesis that children in a transitional state with respect to a concept have available more than one strategy for dealing with that concept and activate those multiple strategies when considering a single problem instantiating the concept. Under this hypothesis, the discordant children would be expected to expend more effort on a task tapping this concept and therefore have less effort left over, leading them to perform worse on the secondary task than the concordant children, as we found they did. Note that in this theory, the availability of more than one strategy in the child's repertoire is *not* what characterizes the child in a transitional state. Rather, it is the fact that both strategies are activated simultaneously on a single problem. It is this simultaneity that presumably generates uncertainty over the appropriate strategy—and that we believe provides the impetus for developmental change.

If our hypothesis is correct, we would expect the discordant children (whose 2-strategy explanations reflect a high level of uncertainty) to be particularly likely to benefit from instruction—indeed, more likely than the concordant children (who activate only one strategy per problem, reflecting far less uncertainty). In fact, this is precisely what we have found. Perry et al. (1988) gave 37 children a pretest comparable to the one used in this study. They then trained all of the children in mathematical equivalence, and gave each child a posttest consisting of addition problems comparable to those on the pretest and a generalization test consisting of multiplication problems. Perry et al. found that the 13 children who were discordant on the pretest were significantly more likely to succeed on the addition problems on the posttest and to generalize their understanding to the multiplication problems, than the 17 children who were concordant on the pretest. Similarly, in a training study of a younger group of children given instruction in conservation, Church and Goldin-Meadow (1986) found that the children who were discordant in their explanations of conservation before training were significantly more likely to improve their performance on the conservation posttest than the children who were concordant before training. Thus, as predicted, the discordant children appeared to be on the verge of acquisition, ready to profit from relevant input, whereas the concordant children were not. In this sense, discordant children can be said to be in a transitional state.

Further support for our hypothesis comes from the fact that the discordant state appears to be transitional not only in the sense that it predicts receptivity to instruction but also in the sense that it is both preceded and followed by a concordant state. Alibali and Goldin-Meadow (1992) asked 63 children to solve and explain a series of problems instantiating the concept of mathematical equivalence (see also Wagner, Scott, Church, & Goldin-Meadow, 1990). The relationship between gesture and speech in each explanation was monitored over the series. Alibali and Goldin-Meadow found that the majority of children who acquired the concept did so by adhering to the hypothesized path: The children first produced a single, incorrect strategy. They then entered a discordant state in which they produced different strategies, one in speech and another in gesture, some incorrect and some correct. Finally, they again closed on a single strategy, but a correct one. These data lend further support to the notion that the transitional state is characterized by the simultaneous availability of more than one strategy.

We recognize that the results of the present study show only that the discordant children performed less well on the 3-word lists accompanying the hard math problems—a result consistent with, but not necessarily proof of, the hypothesized simultaneous activation of more than one strategy. However, we posited this hypothesis in the first place because of findings comparable to those found here on the pretest, where the discordant children were shown to produce 2-strategy explanations six times more often than the

[4] Note that it is not possible to discriminate an Add-All strategy from an Add-to-Equal strategy on Easy problems such as $4 + 7 + 3 + 5 = \_\_\_\_$, because both strategies involve adding all four of the numbers in the problem.

concordant children. In addition, other hypotheses that might account for the discordant children's relatively poor performance find no support in our data, and, in many cases, we found evidence that directly contradicts these alternative explanations. For example, it was possible that the discordant children performed less well on the 3-word lists accompanying the hard math problems because they were more confused about how to solve these problems than the concordant children. However, neither the discordant nor the concordant children were particularly confused in their explanations of the hard problems on the pretest (very few unclassifiable responses were found in either group). Moreover, the discordant children took no longer to solve the hard math problems than the concordant children and thus did not appear to be confused in this sense. In addition, there was no evidence that the discordant children had learned their strategies less well than the concordant children (which might have led them to expend more effort in applying even a single strategy) because there were no differences between the two groups on the easy problems (where all of the children were assumed to activate one strategy per problem). In fact, if anything, the discordant children appeared more knowledgeable about the concept, having produced significantly more correct strategies in gesture than the concordant children. Finally, one might have argued that the discordant children had less working memory capacity than the concordant children and, as a result, did particularly poorly when this capacity was strained on the 3-word lists accompanying the hard problems. However, this argument is difficult to credit given that it is the discordant children who tend to benefit from instruction and readily make progress in the concept, not the concordant children. Thus, we continue to argue that the poor performance of the discordant children on the 3-word lists accompanying hard math problems is best accounted for by the hypothesis that the discordant children activate more than one strategy on a single problem.

The Simultaneous Activation of Two Strategies and Skill Acquisition

In one of the earliest studies of skill acquisition in adults, Crossman (1959) suggested that a learner faced by a new task tries out various methods, and that this multiplicity of methods characterizes the transitional period that precedes mastery of the task. In Anderson's (1982) model of the acquisition of cognitive skill, new productions do not necessarily replace old productions but rather coexist with them; thus there are periods during acquisition when two productions activated by the same conditions can be found in the learner's repertoire. Logan's (1988) model of automatization in the acquisition of skills posits a transition from algorithm-based performance to memory-based performance; during the transition (and perhaps beyond), the learner has in his repertoire two strategies—a general algorithm for solving the problem, as well as a single-step direct-access retrieval of past solutions from memory. Thus, as in descriptions of acquisition in children, descriptions of adult learning frequently posit a multiplicity of strategies in the repertoire of the learner during the period of acquisition.

The question, however, is whether these multiple strategies are activated on a single problem. Logan and Klapp (in press) posit a horse race between the general algorithm and instance-based retrieval: Both strategies are activated, with solution time determined by the more efficient of the two.[5] In Anderson's (1982) model, a production is eligible for activation if its conditions match the information active in working memory. Thus, two productions with the same conditions can indeed be selected and tested for activation on a single problem, with the stronger or more specific production determining the action that is actually executed.

Although both of these models allow for moments in acquisition when two strategies are activated on a single problem, there is nothing in either model that attributes special significance to such periods. In contrast, the results of the study presented here, in conjunction with our previous work, suggest that the periods during which a learner activates two strategies on a single problem (the periods of discordance) are just those periods when the learner is most susceptible to instruction on problems of that type, a feature that could be (and, we would argue, should be) incorporated into models of skill acquisition.

In our studies, we have examined the transition from an incorrect understanding of a concept to a correct understanding. In contrast, many studies of skill acquisition focus on transitions in which knowledge becomes more efficiently processed but does not change in structure (as in the changes that occur when adults progress from an unpracticed state to a more automatic and skilled state, e.g., Bryan & Harter, 1989; Logan, 1985; Shiffrin & Schneider, 1977). The model of transition we have proposed may be less applicable to such transitions. One might imagine that the transition out of a state of imperfectly performed, yet correct knowledge would be quite different from the transition out of a state of predominantly incorrect knowledge. In order to progress out of a state in which the learner has a basically correct strategy, all the learner need do is gain expertise in applying that strategy as a whole, or in applying components of the strategy. The learner need not entertain alternative strategies in order to improve performance because the strategy itself is essentially correct.

Nevertheless, it is possible that the relationship between gesture and speech can provide evidence for even this type

[5] The phenomenon we have described here entails having two different algorithms, each representing a distinct approach to the problem solution. To the extent that the general algorithm and the instance-based retrieval in Logan and Klapp's (in press) model reflect the same approach represented in two different formats (one generated by an algorithm and one stored away as a memory of having performed the strategy that the algorithm generated), the model does not apply to the phenomenon we have described. However, instance-based retrievals are not always based on a stored memory of having performed the algorithm; indeed, in one of the studies they report, Logan and Klapp (in press) asked subjects to rote-memorize a set of facts without ever generating an algorithm. Moreover, it is not always the case that an instance-based retrieval generates the same response as the one generated by an algorithm, suggesting that instance-based retrieval and a general algorithm can indeed represent two distinct approaches to a problem solution.

of transitional state (where the learner has an essentially correct rule which is not yet efficiently processed) as well as for the transitional state we have explored in our studies (where the learner entertains multiple strategies, some correct and some incorrect). Learners who possess a correct rule that is not yet smoothly processed might produce matching information in their simultaneously gestured and spoken explanations of a problem, but the two modalities might not be synchronized in terms of a coding dimension we have not yet examined—timing. For example, in response to the problem, 6 + 7 + 4 = ____ + 4, a child might point to the 6 + 7 while saying, "What I did was . . ." and then point to the solution while saying "added 6 + 7." Although the substantive information contained in speech and gesture is identical (and correct), the response has the flavor of being not entirely integrated and suggests that the strategy may not yet be a smoothly functioning unit.

Mechanisms of Transition

Our study was designed to explore the processes that characterize the transitional state, not to explore the specific mechanisms of transition per se. Nevertheless, our findings constrain the types of transition mechanisms that are possible. Our results suggest that the transitional period between two rule-governed states is characterized by the activation of multiple strategies on a single problem. Our data therefore lend credence to theories that hypothesize internal inconsistencies as an impetus for change and the resolution of those internal inconsistencies as a mechanism for transition (cf. Keil, 1984; Piaget, 1975/1985). In general, our data suggest that any mechanism of change purporting to account for transitions of this sort must involve two different processes: (a) one process that serves to introduce a new strategy into the learner's repertoire and thereby create a transitional state characterized by multiple strategies, and (b) a second process that serves to sort out the multiple strategies in the learner's repertoire and arrive at a single, correct strategy characteristic of concept mastery. In a similar vein, Acredolo and O'Connor (1991) have argued that knowledge originates in the discovery of possibility (i.e., of alternatives), and that our task as researchers is to understand how learners come to recognize possibilities (the first of the above processes) and how they evaluate one possibility against the other and arrive at the decision to endorse one over the other (the second of the above processes).

Although there are undoubtedly occasions when learners resolve their uncertainty by choosing one of their old strategies, this process cannot account for change in all transitions; there are times when the multiple hypotheses a learner considers during transition do not include a correct hypothesis, and thus the learner must generate a new hypothesis in order to progress. For example, Ames and Murray (1982) have shown that nonconserving children exposed to the different, but also nonconserving, reasoning of a peer are able to profit from the opposition of the two wrongs and improve their performance on the conservation task. Similarly, in our study, half of the explanations with gesture–speech mismatches that the discordant children produced contained two strategies leading to incorrect solutions. Indeed, Keil has argued that internal inconsistency need not be resolved by choosing one of the two inconsistent beliefs; rather, it is the inconsistency itself that energizes the learner to construct a new, presumably more adequate, solution to the problems (see also Piaget, 1975/1985).

Note, however, that although our results lend credence to the hypothesis that the transitional state is characterized by the simultaneous activation of two strategies, there is nothing in our data to suggest that it is conflict between these two strategies that energizes change. Indeed, it may be that when given appropriate input, the learner is able to integrate aspects of one incorrect strategy with aspects of another incorrect strategy and arrive at a more correct strategy without experiencing conflict. For example, the most common gesture-speech mismatch in our data contained the Add-All strategy in one modality and the Add-to-Equal strategy in the other modality. In order to generate the Add-All strategy, a child must notice the number on the right side of the equal sign; in order to generate the Add-to-Equal strategy, a child must notice that the equal sign breaks the string of numbers into two parts. Both pieces of information are essential in order to generate a correct strategy. Thus, the child may be propelled forward, not necessarily by a contradiction between the two strategies, but by an integration of the distinct, and complementary, pieces of information in the two strategies (see Halford, 1984).

In addition to constraining the types of transition mechanisms that could account for concept acquisition, our findings also provide a tentative explanation for the frequent observation of regression in the acquisition of concepts. Our data suggest that learners in transition are working under increased cognitive demands and that as a result, there is a cost to being in a state of transition. This further suggests that the transitional state may be an unstable one and likely to be transient. If learners in transition are provided with appropriate input, they might be expected to progress not only to a more stable state but also to a more correct one. This is, in fact, what we have found in our training studies with respect to the acquisition of both conservation (Church & Goldin-Meadow, 1986) and mathematical equivalence (Alibali & Goldin-Meadow, 1992; Perry et al., 1988). However, if learners in transition are not provided with input and if the transitional state is indeed an unstable one, then the learners might be expected to regress to a more stable—but incorrect—state at least as often as, if not more often than, they progress to a stable correct state. Church (1990) charted spontaneous progress in the acquisition of conservation in a group of children over a period of several months and did in fact find that without training, many of the children moved from an incorrect and unstable state to one that was more stable but that was also incorrect (see also Alibali & Goldin-Meadow, 1992).

The Importance of Gesture as a Research Tool

The findings in this study continue to reinforce the usefulness of gesture as a tool for the researcher to explore learners in transition. In previous work, we have shown that the mismatch between gesture and speech in a child's explanations of a concept signals to the researcher that the child is in transition with respect to that concept (Church & Goldin-Meadow, 1986; Perry et al., 1988; 1992).[6] The data presented here further suggest that the explanations children produce to explain their solutions to problems—if both the gestural and verbal components of those explanations are considered—can provide information about the number of strategies children activate when they actually solve the problems. Thus, the mismatch between gesture and speech in a child's explanations predicts ability on a task which has nothing to do with the explanation and, moreover, provides insight into the internal processes that characterize the mind of a child in transition.

In addition, gesture and speech appear to reflect knowledge at different levels. Speech appears to tap knowledge that is relatively explicit. For example, in our study, the strategy a child actually used to solve a pretest problem was the strategy reflected in the child's speech. In contrast, gesture appears to reflect implicit knowledge, strategies that do not yet control the solution to the problem (perhaps because they lack strength or specificity, in Anderson's [1982] terms) but that do put demands on working memory. In addition to putting demands on working memory, the strategies found in gesture also appear to set the agenda for future development. For example, in a training study of conservation, Church and Goldin-Meadow (1986) found that a majority of the children who produced a conservation explanation in speech for the first time on the posttest, had produced that explanation in gesture on the pretest. Thus, what the children said with their hands before training appeared to be what they were most likely to learn during training, which suggests that although the knowledge expressed in gesture may be implicit, it still has an effect on certain levels of behavior.

In addition to providing the researcher with a tool to detect when a learner is in transition, the mismatch between gesture and speech in a learner's explanations may also provide a signal to the individuals with whom the learner interacts, one that makes them aware at some level that the learner is in a transitional state and ready to benefit from instruction. In fact, Goldin-Meadow, Wein, and Chang (1992) have shown that adults who have not been trained to code gesture can detect and interpret the match or mismatch between gesture and speech in a child's explanations. Thus, children's production (or lack of production) of gesture-speech mismatches may provide feedback to those who interact with them, and thereby provide the children (or any learner) with a mechanism through which they can help shape their own learning environments.

In sum, our previous work has shown that children who are in transition with respect to a concept simultaneously produce more than one strategy in a single response when explaining their beliefs about that concept. The data from the present study suggest that the multiple strategies that children in transition express in their explanations are simultaneously processed, and thus demand cognitive capacity, when those children solve problems instantiating that concept. Thus, it is the simultaneous activation of multiple strategies that appears to characterize the transitional state children—and, perhaps, any learner—experience as they acquire a concept.

[6] In terms of the generality of these results, it is important to note that the phenomenon of discordance does not appear to be limited to children. Goodman, Church, and Schonert (1991) have found that, at times, adults also produce mismatches between gesture and speech when asked to explicate their reasoning about moral problems.

References

Acredolo, C. & O'Connor, J. (1991). On the difficulty of detecting cognitive uncertainty. *Human Development, 34,* 204–223.

Acredolo, C., O'Connor, J., & Horobin, K. (1989). *Children's understanding of conservation: From possibility to probability to necessity.* Paper presented at the biennial meeting of the Society for Research in Child Development, Kansas City, MO.

Alibali, M. W., & Goldin-Meadow, S. (1992). *Gesture–speech mismatch and mechanisms of learning: What the hands reveal about the child's state of mind.* Manuscript submitted for publication.

Ames, G. J., & Murray, F. B. (1982). When two wrongs make a right: Promoting cognitive change by social conflict. *Developmental Psychology, 18,* 894–897.

Anderson, J. R. (1982). Acquisition of cognitive skill. *Psychological Review, 89,* 369–406.

Anderson, J. R. (1987). Skill acquisition: Compilation of weak-method solutions. *Psychological Review, 94,* 192–210.

Baddeley, A. D. (1986). *Working memory.* Oxford, England: Oxford Science Publications.

Brown, T. L., & Carr, T. H. (1989). Automaticity in skill acquisition: Mechanisms for reducing interference in concurrent performance. *Journal of Experimental Psychology: Human Perception and Performance, 15,* 686–700.

Brown, J. S., McDonald, J. L., Brown, T. L., & Carr, T. H. (1988). Adapting to processing demands in discourse production: The case of handwriting. *Journal of Experimental Psychology: Human Perception and Performance, 14,* 45–59.

Bryan, W. L., & Harter, N. (1989). Studies of the telegraphic language. The acquisition of a hierarchy of habits. *Psychological Review, 6,* 345–376.

Chase, W. G., & Ericsson, K. A. (1981). Skilled memory. In J. R. Anderson (Ed.), *Cognitive skills and their acquisition* (pp. 227–249). Hillsdale, NJ: Erlbaum.

Chase, W. G., & Simon, H. A. (1973). Perception in chess. *Cognitive Psychology, 4,* 55–81.

Cheng, P. W. (1985). Restructuring versus automaticity: Alternative accounts of skill acquisition. *Psychological Review, 92,* 414–423.

Church, R. B. (1990). *Equilibration: Using gesture and speech to monitor cognitive change.* Paper presented at the Twentieth Anniversary Symposium of the Jean Piaget Society, Philadelphia, PA.

Church, R. B., & Goldin-Meadow, S. (1986). The mismatch between gesture and speech as an index of transitional knowledge. *Cognition, 23,* 43–71.

Crossman, E. R. F. W. (1959). A theory of the acquisition of speed-skill. *Ergonomics, 2,* 153–160.

Ericsson, K. A., & Simon, H. A. (1980). Verbal reports as data. *Psychological Review, 87,* 215–251.

Evans, M. A., & Rubin, K. H. (1979). Hand gestures as a communicative mode in school-aged children. *The Journal of Genetic Psychology, 135,* 189–196.

Flavell, J. H. (1984). Discussion. In R. J. Sternberg (Ed.), *Mechanism of cognitive development* (pp. 19–22). New York: Freeman.

Fischer, K. W. (1980). A theory of cognitive development: The control and construction of hierarchies of skills. *Psychological Review, 87,* 477–531.

Glaser, R., & Bassok, M. (1989). Learning theory and the study of instruction. *Annual Review of Psychology, 4,* 631–666.

Glaser, R., & Chi, M. T. H. (1988). Overview. In M. T. H. Chi, R. Glaser, & M. J. Farr (Eds.), *The nature of expertise* (pp. 36–59). Hillsdale, NJ: Erlbaum.

Goldin-Meadow, S., Wein, D., & Chang, C. (1992). Assessing knowledge through gesture: Using children's hands to read their minds. *Cognition and Instruction, 9*(3), 201–219.

Goodman, N., Church, R. B., & Schonert, K. (1991). *Moral development and gesture: What can the hands reveal about moral reasoning?* Paper presented at the annual meeting of the Jean Piaget Society, Philadelphia, PA.

Halford, G. S. (1984). Can young children integrate premises in transitivity and serial order tasks? *Cognitive Psychology, 16,* 65–93.

Hasher, L., & Zacks, R. T. (1979). Automatic and effortful processes in memory. *Journal of Experimental Psychology: General, 108,* 356–388.

Keil, F. C. (1984). Mechanisms of cognitive development and the structure of knowledge. In R. J. Sternberg (Ed.), *Mechanisms of cognitive development* (pp. 63–86). New York: Freeman.

Klahr, D. (1984). Transition processes in quantitative development. In R. J. Sternberg (Ed.), *Mechanisms of cognitive development* (pp. 41–82). New York: Freeman.

Kučera, H., & Francis, W. N. (1982). *Frequency analysis of English usage: Lexicon and grammar.* Boston, MA: Houghton Mifflin.

Kuhn, D. (1972). Mechanisms of change in the development of cognitive structures. *Child Development, 43,* 833–844.

Langer, J. (1969). Disequilibrium as a source of development. In P. Mussen, J. Langer, & M. Covington (Eds.), *Trends in issues in developmental psychology* (pp. 21–42). New York: Holt, Rinehart & Winston.

Logan, G. D. (1979). On the use of a concurrent memory load to measure attention and automaticity. *Journal of Experimental Psychology: Human Perception and Performance, 5,* 189–207.

Logan, G. D. (1985). Skill and automaticity: Relations, implications, and future directions. *Canadian Journal of Psychology, 39,* 367–386.

Logan, G. D. (1988). Toward an instance theory of automatization. *Psychological Review, 95,* 492–527.

Logan, G. D., & Klapp, S. T. (in press). Automatizing alphabet arithmetic: 1. Is extended practice necessary to produce automaticity? *Journal of Experimental Psychology: Human Perception and Performance.*

Mazur, J. E., & Hastie, R. (1978). Learning as accumulation: A reexamination of the learning curve. *Psychological Bulletin, 85,* 1256–1274.

Miller, S. A., Brownell, C. A., & Zukier, H. (1977). Cognitive certainty in children: Effects of concept, developmental level, and method of assessment. *Developmental Psychology, 13,* 236–245.

Navon, D., & Gopher, D. (1979). On the economy of the human processing system. *Psychological Reveiw, 86,* 214–255.

Newell, A., & Rosenbloom, P. S. (1981). Mechanisms of skill acquisition and the law of practice. In J. R. Anderson (Ed.), *Cognitive skills and their acquisition* (pp. 200–218). Hillsdale, NJ: Erlbaum.

Nisbett, R. E., & Wilson, T. D. (1977). Telling more than we can know: Verbal reports on mental processes. *Psychological Review, 84,* 231–259.

Nusbaum, H. C., & Schwab, E. C. (1986). The role of attention and active processing in speech perception. In E. C. Schwab & H. C. Nusbaum (eds.), *Pattern recognition by humans and machines: Speech perception, Volume 1* (pp. 144–165). New York: Academic Press.

Perry, M., Church, R. B., & Goldin-Meadow, S. (1988). Transitional knowledge in the acquisition of concepts. *Cognitive Development, 3,* 359–400.

Perry, M., Church, R. B., & Goldin-Meadow, S. (1992). Is gesture–speech mismatch a general index of transitional knowledge? *Cognitive Development, 7,* 109–122.

Piaget, J. (1985). *The equilibration of cognitive structures.* Chicago: The University of Chicago Press. (Original work published 1975)

Posner, M. I. (1978). *Chronometric explorations of mind.* Hillsdale, NJ: Erlbaum.

Shiffrin, R. M. (1976). Capacity limitations in information processing, attention, and memory. In W. K. Estes (Ed.), *Handbook of learning and cognitive processes, Volume 4* (pp. 469–487). Hillsdale, NJ: Erlbaum.

Shiffrin, R. M., & Schneider, W. (1977). Controlled and automatic human information processing: II. Perceptual learning, automatic attending, and a general theory. *Psychological Review, 84,* 127–190.

Siegler, R. S. (1981). Developmental sequences within and between concepts. *Monographs of the Society for Research in Child Development, 46*(Whole No. 189).

Siegler, R. S. (1983). Five generalizations about cognitive development. *American Psychologist, 38,* 263–277.

Siegler, R. S., & Jenkins, E. (1989). *How children discover new strategies.* Hillsdale, NJ: Erlbaum.

Snyder, S. S., & Feldman, D. H. (1977). Internal and external influences on cognitive developmental change. *Child Development, 48,* 937–943.

Stigler, J. W., Nusbaum, H. C., & Chalip, L. (1988). Developmental changes in speed of processing: Central limiting mechanism or skill transfer? *Child Development, 59,* 1144–1153.

Strauss, S. (1972). Inducing cognitive development and learning: A review of short-term training experiments. I. The organismic developmental approach. *Cognition, 1,* 329–357.

Strauss, S., & Rimalt, I. (1974). Effects of organizational disequilibrium training on structural elaboration. *Developmental Psychology, 10,* 526–533.

Turiel, E. (1969). Developmental processes in the child's moral thinking. In P. Mussen, J. Langer, & M. Covington (Eds.), *Trends and issues in developmental psychology* (pp. 117–141). New York: Holt, Rinehart & Winston.

Turiel, E. (1974). Conflict and transition in adolescent moral development. *Child Development, 45,* 14–29.

Wagner, M. M., Scott, M., Church, R. B., & Goldin-Meadow, S. (1990). *Disequilibrium in concept acquisition: What the hands reveal about a child's state of mind.* Paper presented at the Twentieth Anniversay Symposium on the Jean Piaget Society, Philadelphia, PA.

Walker, L. J., & Taylor, J. H. (1991). Stage transitions in moral reasoning: Longitudinal study of developmental processes. *Developmental Psychology, 27,* 330–337.

Received July 12, 1991
Revision received February 12, 1992
Accepted March 5, 1992 ■