DOCUMENT RESUME

ED 343 783 SE 052 461

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TITLE Transitions in Learning: Evidence for Simultaneously Activated Strategies.
SPONS AGENCY National Inst. of Child Health and Human Development (NIH), Bethesda, MD.
PUB DATE Apr 91
CONTRACT R01HD18617
NOTE 20p.; Paper presented at the Biennial Meeting of the Society for Research in Child Development (Seattle, WA, April 18-20, 1991).
PUB TYPE Reports - Research/Technical (143)

EDRS PRICE MF01/PC01 Plus Postage.
DESCRIPTORS *Cognitive Development; *Cognitive Dissonance; *Concept Formation; *Elementary School Mathematics; Grade 4; Intermediate Grades; Mathematical Concepts; Mathematics Education; Mathematics Skills; Number Concepts; Problem Solving; *Thinking Skills
IDENTIFIERS *Conceptual Change; *Conceptual Frameworks; Mathematics Education Research

ABSTRACT

Children rarely cite more than one strategy when asked to explain how they solved a particular arithmetic problem, hence their verbal explanations will not necessarily reveal whether they have considered multiple strategies on that problem. However, previous work has shown that, when asked to explain their performance on a task, children often use gestures along with their spoken explanations, and these gestures convey substantive information about the completion of that task which is different from the verbal information. While solving a primary, arithmetic task as part of this study, discordant children (n=7) who produced explanations with different strategies in gesture and speech, and concordant children (n=10) who produced explanations with a single strategy were both given a secondary task, or cognitive load. Discordant and concordant children alike produced the same number of correct responses on the primary task. However, as predicted, the discordant children expended more effort on the primary task due to the activation of two strategies, thereby reducing their capacity to perform on the secondary task in comparison with the concordant children. Discussion focuses on the suggestion that the transitional knowledge state with respect to conceptual attainment in the young learner appears to be characterized by multiple representations which are simultaneously held in the same mental space and are activated when the learner attempts to actively engage in problem solving. (JJK)

Transitions in Learning:

Evidence for Simultaneously Activated Strategies

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April 1991

Paper presented as part of a symposium on transitional knowledge at the biennial meeting of the Society for Research in Child Development, Seattle, WA.

This research was supported by Grant #RO1 HD18617 from the National Institute of Child Health and Human Development to S. Goldin-Meadow, and by funds from the Smart Foundation. We thank Miriam Bassok, Janellen Huttenlocher, Susan Levine, and Jim Stigler for insightful comments in discussions of the work and the manuscript, and Martha Wagner and Jill Morford for their help in designing and conceptualizing the study.

ABSTRACT

Previous work has shown that 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. This study asks whether both strategies are activated when the child solves problems instantiating the concept. While solving a primary math task, children who produced explanations with different strategies in gesture and speech (discordant children) and children who produced explanations with a single strategy (concordant children) were both given a secondary (cognitive load) task. Discordant and concordant children produced the same number of correct responses on the primary task. However, we predicted that if discordant children are activating two strategies on the primary task and maintaining those strategies in working memory, they will expend more effort on this task than concordant children; consequently, discordant children will have less capacity left over for the secondary task, thereby reducing their performance on this task relative to the performance of concordant children. This prediction was confirmed, suggesting that the multiple strategies that a child in transition expresses when explaining a concept are simultaneously activated, and as a result demand cognitive capacity, when the child solves problems instantiating that concept. Thus, the transitional knowledge state appears to be characterized by multiple representations which are simultaneously held in the same mental space and activated when attempting to 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. 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 rules to more intuitive, pattern recognition (see Glaser & Chi, 1988). For example, chess novices apply rules one after another 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 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 novice (i.e., rule 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).

Similarly, in research on skill acquistion, 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 effectively; the only changes that occur are in the efficiency with which this knowledge is employed.

In contrast to this work on learning in adults, research in developmental psychology has acknowledged, and even stressed, the importance of understanding the period of transition in learning (e.g., Flavell, 1984). However, in spite of explicitly acknowledging the importance of understanding the transitional period, 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.

Indeed, 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 a concept is, throughout the period of acquisition, systematic and rule-governed. For example, 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. If, as findings of this sort suggest, the acquisition of a concept is best characterized as a progression from one (presumably inadequate) rule or strategy to another (more adequate) rule or strategy, it becomes even more important to ask how children make the transition from one rule-governed state to the next. The purpose of the present study is to probe the cognitive processes that characterize the transitional state in children acquiring the concept of equivalence.

Transition in the acquisition of concepts: the role of multiple strategies. Although it is possible that children 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. 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 allows the child to directly compare and contrast those strategies and thus 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 solves 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 & 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 of 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 rules that specify how a skill is transformed into a new, more advanced skill; each of these rules 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 rules -- rules 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 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). 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. 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 considers both strategies before choosing one (and thus may be in state of uncertainty or conflict on each problem), it is not necessarily the case that the child is simultaneously considering the two strategies. 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 conflict or 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 has chosen one of the two) that we can be confident the child has experienced internal conflict or 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 attain 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, although they may be considering those strategies sequentially rather than simultaneously. The question we adress here is whether children spontaneously consider more than one strategy when solving and explaining the problem on their own, and whether they consider those strategies simultaneously.

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 often gesture along with their spoken explanations, and these gestures convey substantive information about the task itself (e.g., Evans & Rubin, 1979). Our previous work has shown that, while gesture frequently conveys the same information as conveyed in speech and thus matches 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 gestured spontaneously while speaking and used those gestures to convey specific strategies that described how to solve the problem. Often 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, the gestures produced by the children did not always 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 speech and a different strategy in gesture, suggesting that they not only had two strategies in their repertoire but that they also considered those strategies simultaneously on 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). Thus, the discordant children -- who gave evidence of considering two 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 strategy on a problem -- were not (see Church & Goldin-Meadow, 1986, for comparable results with respect to conservation).

In addition, Wagner, Scott, Church and Goldin-Meadow (1990) gave a group of fourth grade children extensive instruction in mathematical equivalence and observed their explanations (given after problem solutions) throughout the training period. Wagner et al found that, as they acquired the concept of mathematical equivalence, children progressed through a series of steps. Explanations first consisted of a single, incorrect strategy (exhibited in speech alone or both gesture and speech). The children then proceeded through a period when their explanations consisted of two strategies, either two incorrect strategies or one correct and one incorrect strategy (one in gesture and one in speech). In the final stage, the explanations again consisted of a single strategy (in speech alone or in both gesture and speech) but this time the strategy was correct.

These data further suggest that one characteristic of the transitional period in the acquisition of a concept is the production of more than one strategy within a single explanation.

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 consider two strategies when explaining how they solved a problem does not necessarily mean that the children consider both strategies when actually solving the problem. 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, in addition to having communicative consequences reflected in the explanations of children in transition, 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). Nusbaum and Schwab (1986) have argued that increased demands on cognitive capacity will occur whenever there is a space of 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. Similarly, interpreting a polysemous word (e.g., bank) could require more capacity than interpreting a word with a single meaning (e.g., money). In terms of solving a problem, if more than one strategy or solution is possible, evaluation of the space of multiple solutions should require more capacity than evaluating a single strategy for a different problem.

Nusbaum and Schwab (1986) have argued that in the most general terms, there are two types of capacity that could be used in cognitive operations, time and space. Time is used as a resource whenever a set of alternative strategies or interpretations are evaluated one after another. If a set of strategies is evaluted in sequence, the longer the sequence, the longer the time to generate a response. On the other hand, space will be required as a resource if a set of strategies is evaluated simultaneously. Either more processes will be invoked in parallel, or more memory capacity will be required to simultaneously maintain the activated strategies. If a set of problem strategies or perceptual hypotheses are evaluated simultaneously, there is a good chance that there will be increased demands on working memory to keep those hypotheses available for evaluation. As the size of the set of hypotheses increases, the demands on working memory will also increase.

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. In effect, a child who activates multiple strategies on one task should have less capacity left over to simultaneously perform a second (unrelated) task than a child who activates only a single strategy.

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 math task and on a simultaneously performed secondary word recall task. 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. 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 (cf., Baddeley, 1986).

It is possible, of course, that children's explanations of a concept have nothing to do with the way they solve problems instantiating that concept. If so, we would expect no difference in performance on either the primary math task or the secondary word recall task between children who are discordant on the explanation pretest and children who are concordant. Alternatively, children's explanations may indeed be related to the way they solve problems. If so, children who are discordant in their explantions of mathematical equivalence would be expected to solve problems differently from children who are concordant in their explanations. Two outcomes are then possible, each predicated on a different view of the transitional knowledge state. The first is that children who are discordant in their explanations of mathematical equivalence -- and who have been shown to be in a transitional state with respect to this concept (cf., Perry et al, 1988) -- are in that transitional state because they are more facile with numbers and addition than children who are concordant in their explantions (i.e., although not masters of the math task, they are hypothesized to be somewhat more competent on the task than the concordant children). Under this view, we would expect the discordant children to expend less effort on the primary math task and thus to have enough working memory left over to allow them to perform better on the secondary word recall task than the concordant children. The second view, and the one that we propose here, is that what puts discordant children into a transitional state with respect to mathematical equivalence is the fact that they activate two strategies on a single problem problem instantiating the concept. Our prediction is therefore that the discordant children should expend more effort on the primary math task and, as a result, have in a decrement in working memory which leads them to perform less well on a secondary word recall task than the concordant children (who activate a single strategy).

METHOD

Subjects

Seventeen 4th grade students (7 female and 10 male) from a parochial elementary school in Chicago participated in the study. Three children who were successful on two 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, particularly those who were on the verge of acquiring the concept. The remaining 17 children comprised the subjects for the study and ranged in age from 9;4 (years;months) to 10;6 (mean age = 10;0).

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 examiner left the room and a second examiner accompanied the child to the chalk board. 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

Before each math problem, the child was presented with a word list (see below) that was to be recalled after the math problem had been solved. Each child was asked to solve (but not explain) 24 addition problems of two types: (1) 12 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.[1] (2) 12 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 to 9). Given the types of explanations concordant and discordant children produce when explaining their solutions to problems of this type, 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 each math problem, the child was given a list of words and asked to recall the words after solving the problem. On each trial, the experimenter read the list of words 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: (1) a 1-word list which was expected to put relatively little strain on the child's capacity and thus was considered a condition of low cognitive load, and (2) a 3-word list which 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 Kucera 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, as were the Easy math problems. The order in which the four sets of six problems were presented was randomized.

Coding and Analysis

Videotapes of the explanations the children produced during the pretest were analyzed according to the gesture/speech coding system described in detail in Perry et al (1988). Two independent observers coded each explanation, one determining the strategy expressed in speech and the other determining the strategy expressed in gesture. A third coder then determined whether the strategy conveyed in gesture matched the strategy conveyed in speech. Following Perry et al,

[1] In a pilot study of 12 children who had not yet acquired mathematical equivalence, we found that all 12 of the children were, in fact, concordant when they explained these Easy problems. Note that this means that the children who were discordant when they explained the Hard problems (7 of the 12 children in this sample) did not have the same concordance/discordance status on the two types of problems, confirming once again (cf., Perry et al, 1988) that discordance is not a characteristic of the child but rather a characteristic of the cognitive processes activated at the time of solving a problem.

children who produced 3 or more responses 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 produced gesture on all but one of their 90 explanations).

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 2, although less pronounced, remains the same).

All of the data were analyzed using 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.

RESULTS

Pretest Performance

On the basis of the six explanations they produced on the pretest, the 17 children were divided into two groups: 10 children, whose number of gesture-speech mismatches ranged from 0 to 2 (mean=0.80), were classified as concordant (7 boys and 3 girls), and 7 children, whose number of gesture-speech mismatches ranged from 3 to 6 (mean=3.6), were classified as discordant (3 boys and 4 girls). The concordant children ranged in age from 9;9 to 10;3 (mean age=10;1), and the discordant children ranged in age from 9;4 to 10;6 (mean age=10;0).

None of the concordant children produced correct solutions on the six pretest addition problems, and only one discordant child produced a correct solution on one of the six pretest problems. All of the spoken explanations produced by both concordant and discordant children conveyed nonequivalence strategies (that is, solution strategies which would lead to the sum on the right side of the equation being different from the sum on the left side of the equation). Although most of the explanations produced in gesture also conveyed nonequivalence strategies, the children produced a small number of gestured explanations that conveyed equivalence strategies (that is, solution strategies which would lead to the sum on the right side of the equation being equal to the sum on the left side). Six children produced these gestured equivalence strategies: 5 of the 6 were discordant and produced equivalence strategies in 8 (47%) of their 17 gesture/speech mismatches (27% of their total explanations), and 1 was concordant and produced an equivalence strategy in his one gesture-speech mismatch (note that these 6 children solved the addition problems incorrectly on the pretest, i.e., they gave nonequivalence solutions on the problems; thus, the equivalence strategies given in their gestured explanations did not describe the way they actually solved the problems).

Performance on the Math Problems (the Primary Task)

Figure 1 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 on the Hard math problems. Performance on the Easy problems was significantly higher than on the Hard problems

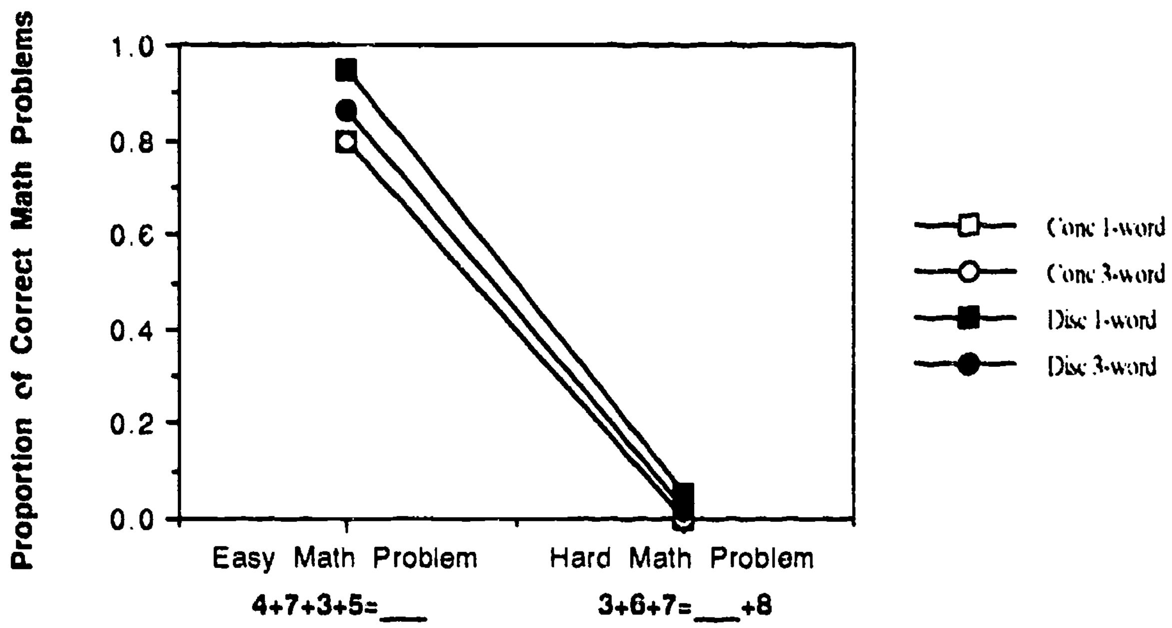

Figure 1. Performance on the Math Problems (the Primary Task). The figure presents the proportion of Easy and Hard math problems solved correctly by concordant and discordant children under conditions of low (1-word list) and high (3-word list) cognitive load.

($F(1,15)=384.75$, $p<.001$) and there was no effect of concordant vs. discordant status ($F(1,15)=2.74$, $p=.19$) or of low vs. high cognitive load ($F(1,15)=1.70$, $p=.21$).

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 utilizes 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 2 presents the proportion of word lists presented 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. Looking first at main effects, we found an overall effect of list length on recall; that is, performance on the 1-word lists was significantly better than on the 3-word lists ($F(1,15)=32.87$, $p<.001$). There was no overall effect of concordant vs. discordant status ($F(1,15)=2.50$, $p=.14$) or of easy vs. hard math problems ($F(1,15)=1.37$, $p=.26$).

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 ($F(1,15)=.17$, $p=.69$).

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 ($F(1,15)=.066$, $p=.80$).

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 when solving the Hard math problems (on which they were expected to activate two strategies) than they themselves did when solving the Easy math problems (on which they were expected to activate only one strategy, $F(1,15)=5.52$, $p<.03$). In addition, when solving the Hard math problems under conditions of high cognitive load, the discordant children (who were expected to active two strategies) performed significantly less well on the word lists than did the concordant children (who were expected to activate only one strategy, $F(1,15)=8.86$, $p<.01$).

DISCUSSION

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. 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

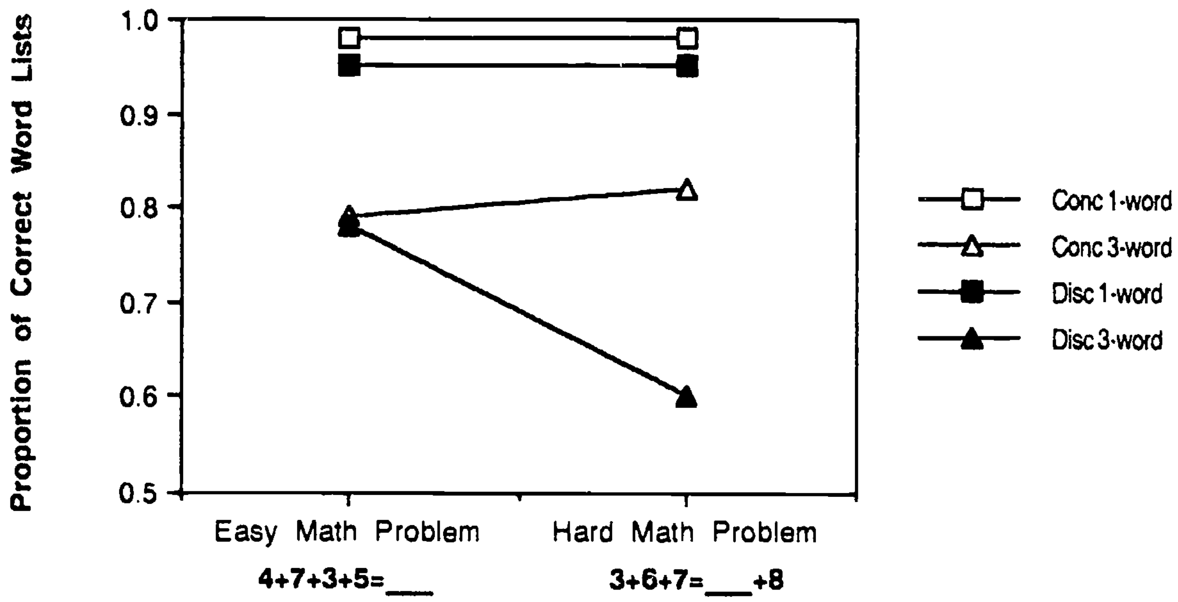

Figure 2. Performance on the Word Lists (the Secondary Task). The figure presents the proportion of word lists preceding Easy and Hard math problems that were recalled correctly by concordant and discordant children under conditions of low (1-word list) and high (3-word list) cognitive load.

problems instantiating that concept. Moreover, the data from this study bear on the question of what it means for a child to be in a transitional state. The results distinguish between two distinct views of the transitional state: (1) 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. (2) 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 the availability of more than strategy per se 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, thus allowing direct comparison between the strategies. It is this direct comparison which presumably generates uncertainty and internal conflict over the appropriate strategy and which we believe provides the impetus for developmental change.

Simultaneous activation of multiple strategies in solving problems and in communicating about concepts. The simultaneous activation of multiple strategies, if a characteristic of the transitional state, should have detectable consequences (1) in the way children in transition with respect to a concept solve problems instantiating that concept and, perhaps, (2) in the way they communicate about the concept as well. In terms of solving problems, we might expect children in transition with respect to a particular concept, if they do indeed activate multiple strategies when considering that concept, to expend considerable effort when they solve problems instantiating the concept. Thus, we would expect there to be a cost associated with being in a transitional state. The results of the present study show evidence of this cost in the increased demands on working memory. We found that, when children in transition with respect to a concept solved problems instantiating that concept, they arrived at the same answers to the problems as children who were not in transition; however, they expended more effort in solving those problems -- as indicated by the fact that they had less working memory left over for a second task and thus performed more poorly on that task. The cost of being in a transitional state may also be evident in the amount of time it takes children in transition to solve problems. For example, Siegler and Jenkins (1989), in their microgenetic study of how children discover addition strategies, found that, on the trials before a strategy was produced for the first time (that is, at a point of transition), children took a particularly long time to solve the problem -- a delay which Siegler and Jenkins attributed to conflict or interference among competing strategies.

In terms of communicating about concepts, we might expect children in transition, not only to provide evidence of more than one strategy in their explanations of a concept, but also to provide evidence of confusion or uncertainty in those explanations. Our previous work has shown that children in transition with respect to a particular concept produce more than one strategy (one in speech and one in gesture) when explaining their solutions to problems instantiating that concept (Church & Goldin-Meadow, 1986; Perry et al, 1988; Wagner et al, 1990). Siegler and Jenkins (1989) have shown that, at the point when children first use a new strategy, they become inarticulate and appear confused, particularly when their verbal explanations are considered in conjunction with their performance on the task itself. For example, children at the transitional point were found to, at times, produce strategy descriptions that were partially consistent with overt behavior on the trial and partially inconsistent, e.g., one child was heard counting "4, 5, 6, 7," but revealed a different strategy in her self-report, saying that she counted "3, add one is 4, add one is 5, add one is 6, add one is 7, add one is 8." There was consequently evidence in the children's communications, not only for multiple strategies, but also for the confusion that can result from considering those strategies on the same problem. Thus, the simultaneous activation of multiple strategies appears to be a characteristic of the transitional state -- one which puts strain on the way children in transition with respect to a concept solve problems instantiating that concept, and one which also affects the way the children communicate about the concept.

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 state is characterized, not only by the activation of multiple strategies, but more particularly by simultaneous activation of those strategies.

There are basically two ways in which the different strategies (that are displayed simultaneously in speech and gesture in explanations) might be examined during problem solution. Children might either evaluate the strategies sequentially or simultaneously, and these alternatives make different predictions about the demands on working memory that occur while solving problems (cf. Nusbaum & Schwab, 1986). If discordant children considered sequentially first one strategy followed by another, the amount of time required to solve problems should increase compared to concordant children who need only consider a single strategy. However, this should not increase the demands on working memory since only a single strategy would be activated at one time for both the concordant and discordant children.

On the other hand, if the discordant children activate two or more alternative strategies in working memory for simultaneous evaluation, they should have less surplus working memory capacity available than concordant children who activate only a single strategy. Thus, word recall performance in the secondary task is, in essence, a barometer of the demands on working memory during problem solution. The present results show that working memory demands are much higher for the discordant children solving difficult problems than they are for the concordant children solving the same problems (in spite of equivalent performance on these problems). Thus, the increased demands on working memory for the discordant children suggest that during problem solving several strategies were actively considered.

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., Piaget, 1975/1985; Keil, 1984). In general, our data suggest that any mechanism of change purported to account for concept acquisition in children must involve two different processes: (1) one process which serves to introduce a new strategy into the child's repertoire and thereby create a transitional state characterized by multiple strategies, and (2) a second process which serves to sort out the multiple strategies in the child'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 children 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 children 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 child considers during transition do not include a correct hypothesis, and thus the child 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 nonequivalence strategies, that is, both of the strategies the children in transition conveyed were incorrect. Thus, what seems to be the essential component of the transitional state is the simultaneous activation of multiple strategies, regardless of whether those strategies are right or wrong. 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 which energizes the child to construct a new, presumably more adequate, solution to the problem (see also Piaget, 1975/1985).

In addition to constraining the types of transition mechanisms that could account for concept acquisition in children, our findings also provide a tentative explanation for the frequent observation of regression in the acquisition of concepts. Our data suggest that children 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 children 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 (Perry et al, 1988; Wagner et al, 1989). However, if children in transition are not provided with input and if the transitional state is indeed an unstable one, then the children 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.

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 children 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; in press). 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 explanation and, moreover, provides insight into the internal processes that characterize the mind of a child in transition.

It is also worth noting that the mismatch between gesture and speech in a child's explanations could provide a signal to the adults and peers with whom the child interacts, one that makes them aware at some level that the child is in a transitional state and ready to benefit from instruction. In fact, Goldin-Meadow, Wein and Chang (in press) 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 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 experience as they acquire a concept.

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