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MECHANISMS OF TRANSITION: Learning with a Helping Hand

Susan Goldin-Meadow and Martha Wagner Alibali

Learning involves change from a less adequate to more adequate understanding of a task. Although it is important to describe the learner's state before and after the task has been mastered, characterizing the transitional period that bridges these two states is, in a sense, the key to understanding learning. Unfortunately, the transitional period has proved to be difficult to study for several reasons. First, the transitional period is likely to be fleeting or, at the least, more ephemeral than the beginning and end states that anchor it. Second, the transitional period is difficult to identify before the fact. It is easy to identify a learner as having been in transition *after* a task has been mastered—the learner who made progress and succeeded on the task was "in transition" with respect to the task, whereas the learner who failed to make progress was not. However, such a post hoc measure is of limited usefulness, both for experimenters interested in exploring the transitional period and for teachers interested in identifying learners who might be in a transitional period and therefore particularly receptive to instruction.

The purpose of this chapter is to present a measure of the transitional period that is not post hoc, and to describe the findings on transitions in learning that this measure has allowed us to discover. We begin with the phenomenon upon which the measure is based—the mismatch between gesture and speech.

Consider a child who is participating in a Piagetian liquid conservation task and is asked to explain why he thinks the quantities in the two contain-

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ers are different in amount. The child says "they're different because this one is tall and this one is short," while indicating with his hands the height of each container (he holds a flat, horizontal palm at the brim of the glass and then moves his palm to indicate the shorter height of the dish). Such a child has justified his belief that the amounts are different by focusing on the heights of the containers, and has done so in both speech and gesture.

Now consider a second child, also asked to explain why she thinks the quantities in the two containers are different in amount. This child sounds just like the first child, offering in speech the same justification based on the height of the two containers, "they're different because this one is tall and this one is short." However, in gesture, the child conveys different information—she indicates with her hands the width of each container (she holds two flat, vertical palms at the sides of the glass and then moves her palms to indicate the larger width of the dish). This child has justified her belief that the amounts are different by focusing on the heights of the containers in speech, but on the widths of the containers in gesture.

The first point to notice is that one can, on a single task, say one thing and gesture another—a phenomenon we have labeled "gesture–speech mismatch" (Church & Goldin-Meadow, 1986). Such mismatches are not limited to a certain age and a certain task. Gesture–speech mismatches have been observed in preschoolers learning to count (Graham, 1994), elementary school children reasoning about mathematics problems (Alibali & Goldin-Meadow, 1993; Perry, Church, & Goldin-Meadow, 1988), middle-schoolers reasoning about seasonal change (Crowder & Newman, 1993), children and adults reasoning about moral dilemmas (Goodman, Church, & Schonert, 1991), adolescents reasoning about Piagetian bending rods tasks (Stone, Webb, & Mahootian, 1992), and adults reasoning about gears (Perry & Elder, 1994).

The second point to note is that the two children appear to be equally knowledgeable (or unknowledgeable) about conservation of liquid quantity when we listen to their speech. However, as we will show in a later section, if the two children are given instruction in conservation, the child who produces gesture–speech mismatches will be more likely to benefit from instruction than the child who produces gesture–speech matches (Church & Goldin-Meadow, 1986). Thus, gesture–speech mismatch appears to identify children who are ready to profit from instruction in conversation; that is, it identifies children who are "in transition" with respect to this concept.

This article will be divided into four parts. In the first, we provide evidence that gesture–speech mismatch is, in fact, a reliable index of the transitional period. In this first section, we argue that mismatch is not just an epiphenomenon associated with the transitional period but rather reflects a fundamental characteristic of the transitional state. In the second section, we explore the sources of gesture–speech mismatch, arguing that if mismatch is central to the transitional period, the factors that create mismatch might also be the factors that render a learner transitional. In the third section, we explore the role that gesture–speech mismatch plays in the learning process. We argue that gesture–speech mismatch, occurring as it does in naturalistic contexts of communication, may provide a signal to those who interact with the learner, announcing to those who can interpret the signal that the learner is in transition and thus is ready to learn. Finally, we close with a discussion of how information is represented in gesture and speech.

I. Gesture–Speech Mismatch as an Index of Transition

Our claim that gesture–speech mismatch is an index of transition is not meant to apply exclusively to learning during childhood. However, all of our empirical work has thus far been done with children. The studies described in this article therefore focus on children, and leave as an open (and testable) question whether gesture–speech mismatch identifies learners in transition throughout the life span. We begin with a brief review of the central findings in developmental psychology that serve as a basis for current theories of how change occurs.

A. Consistency vs. Variability within the Learner

1. *The Child as Consistent Thinker*

One of Piaget's major contributions to developmental psychology was the observation that children's knowledge is systematic and rule governed, even when that knowledge is incorrect or incomplete. Thus, the period prior to mastery of a concept can be described and related in a systematic way to the period following mastery.

Piaget described the developmental paths that children take when acquiring a concept, and he argued that all children tend to follow a common series of steps in acquiring a particular concept—in other words, there is consistency across children. Moreover, according to Piaget, each step within this common developmental path can be characterized by a single strategy that children typically use when solving problems instantiating the concept. For example, in his description of conservation, Piaget portrayed children as first focusing on a single dimension in the conservation task, then focusing alternately on two dimensions, and finally focusing on the transformation (Piaget, 1964/1967). Thus, in the Piagetian view, there is not only consistency across children but consistency within the child as well.

Following Piaget, developmental studies of a large number of tasks have attempted to document the sequence of states through which children's thinking progresses over developmental time, and to identify *the* strategy that characterizes each state in the series. For example, studies of children's acquisition of simple addition have depicted children as first relying on counting from one, then relying on counting from the larger addend, and finally relying on retrieval (Ashcraft, 1987). Studies utilizing information integration methodology have claimed that children progress from additive to multiplicative strategies in solving balance scale problems (Wilkening & Anderson, 1982) and in making perceptual judgments of area, volume, and velocity (Anderson & Cuneo, 1978; Wilkening, 1980, 1981). An alternate account of the development of area judgment—but one that still argues for commonality across children and a single strategy at each developmental step—claims that children initially center on one side of a rectangle, later are influenced by the covariation between area and shape, and finally reach perceptual constancy (Gigerenzer & Richter, 1990).

Other studies have been specifically designed to identify the rules children use at various points in a developmental progression. Siegler (1976) developed his rule assessment methodology with this goal in mind. For each type of problem that he investigated, Siegler identified a set of possible rules that children could use to solve that type of problem, and devised a set of test problems that would yield a different pattern of correct answers and errors for each possible rule. In this way, the specific rule that a child used in solving the problems could be unambiguously determined. In a research program that investigated a variety of Piagetian tasks, including balance scale problems, projection of shadows problems, and probability problems, Siegler (1976, 1981) showed that, at all points in the developmental progression characterizing each task, most children could be classified as using a single "rule."

Thus, historically, developmental research has emphasized consistency across children and, equally if not more important, consistency within each child. Note that this characterization of the child implies that the process of developmental change will be abrupt and characterized by a total transformation in the child's thinking. The child entertains a single strategy for some period of time, and then (often with no apparent change in environmental circumstances) adopts a completely distinct strategy. As Siegler (1994a) pointed out, portraying children's thinking and knowledge as monolithic for a period of time creates a need to explain the wide gulfs between the strategy used at one point in development and the strategy adopted at a later point.

2. *Theoretical Accounts That Posit Variability within the Child*

In fact, it is somewhat odd that the emphasis in developmental studies has been on *consistency* within the child because many of the major theoretical accounts of developmental change assume *variability* within the child as one of the conditions for change. Even Piaget, a pioneer of the view of the child as consistent thinker, proposed a mechanism for change that relies on variability within the child. For example, Piaget's (1975/1985) theory of equilibration posits that the impetus for transition comes from disequilibrium, which is the result of "internal conflict" between competing approaches to a problem. In the Piagetian view, variable approaches to a problem become integrated into a more advanced approach via the process of equilibration. Within the Piagetian tradition, Langer (1969), Snyder and Feldman (1977), and Strauss (1972; Strauss & Rimalt, 1974) have argued that during transitional periods, children display at least two functional structures with respect to a concept. The children's appreciation of discrepancy between those functional structures leads to disequilibrium, which then serves as the impetus for change. Turiel (1969, 1974) has advanced similar arguments regarding changes in moral reasoning.

Other, non-Piagetian theorists have also argued that variability may motivate or characterize transition. Among information-processing theorists, Klahr (1984; Klahr & Wallace, 1976) has posited conflict-resolution rules as a mechanism of change in self-modifying production systems. These rules are set into action when two productions are eligible to be activated on a single problem. Thus, in Klahr's model, variability serves as a trigger that sets special "change" rules into action. The rules act to strengthen weights that apply to "good" (adaptive or effective) productions and to weaken weights that apply to ineffective, less adaptive productions, so that useful strategies are maintained in the repertoire, and poor ones fade away.

Dynamical systems theories of development have also suggested that variability may characterize transition points. Specifically, one empirical prediction derived from dynamical systems theory is that, when a system goes from one stable (attractor) state to another, the transition should be characterized by greater fluctuation or variability in the behavioral measure, compared to a baseline (Thelen, 1989). For example, during the changes from consistent reliance on a "compare length" strategy for solving number conservation problems to consistent reliance on a "count items" strategy, a child's performance should become more variable. It is not clear whether, within the dynamical systems framework, variability is causally related to change or is merely epiphenomenal to change. However, as in the Piagetian and information-processing accounts, within the dynamical systems framework, when change occurs, variability should be observed.

3. *Empirical Evidence Indicating Variability within the Child*

Recent studies have begun to focus explicitly on documenting and quantifying variability within a child (e.g., Acredolo & O'Connor, 1991; Acredolo, O'Connor, & Horobin, 1989; Crowley & Siegler, 1993; Siegler, 1984; Siegler & Jenkins, 1989; Siegler & McGilly, 1989). What was heretofore considered "noise" in the data, when viewed from a perspective that focused on consistency within the child, is now recognized as data of particular interest from a perspective that focuses on variability within the child. Indeed, variability has been found within an individual child when the child is asked to solve a set of related problems. For example, despite the claims that 5-year-olds think of number conservation solely in terms of the lengths of the rows, trial-by-trial assessments indicate that most 5-year-olds rely sometimes on the lengths of rows, sometimes on the type of transformation, and sometimes on other strategies such as counting or pairing (Siegler, 1995). Evidence of variability within an individual child is not limited to Piagetian tasks but can be found across a wide variety of domains, ranging from language and reading to motor development (see Siegler, 1994b, Table 1). Variability has even been found when a child is asked to solve the same problem twice. For example, a preschooler presented with the identical addition problem on two successive days quite often will use different strategies on the two days (Siegler & Shrager, 1984). Variability on the same problem has also been observed within an individual child in time-telling tasks (Siegler & McGilly, 1989) and in block-building tasks (Wilkinson, 1982).

Although it is interesting that variability can be found within a child over trials, it is not variability alone that provides the impetus for change in the theoretical accounts described above. According to the Piagetian and information-processing accounts described above, more than one strategy must be activated *on a single problem* in order for change to be likely. Under this view, what propels a child forward is not the mere availability of more than one strategy in the child's repertoire, but rather the *concurrent* activation and evaluation of those strategies. However, a child who uses one strategy the first time she solves an addition problem and a second strategy the next time she solves the same problem might not ever consider those two strategies concurrently. Thus, the real question is whether we find variability within a child even on a single problem.

Evidence of variability on a single problem has been particularly difficult to obtain in part because the "forced choice" techniques frequently used in developmental research encourage children to choose or report a single solution for each problem. In an attempt to circumvent this methodologic deficiency, Acredolo et al. (1989) offered children a variety of answers to

a single conservation problem and asked the children to evaluate each answer (some of which were wrong, i.e., nonconserving) using a probability scale. On a number conservation problem, one-third of a group of kindergarten through sixth-grade children accepted (i.e., assigned nonzero probabilities to) more than one of three possible solutions. On an area conservation problem, close to three-quarters of the same group of children accepted more than one solution. These results demonstrate that, when pressed, many children are willing to consider more than one solution to a single problem. However, the data still do not allow us to determine whether individual children *spontaneously* consider several solutions within the same problem.

One technique that can yield evidence about within-problem variability in children's reasoning involves examining *both* what a child says and what he or she gestures when explaining a problem. Indeed, when we examine the gestures that children produce along with their spoken explanations of a problem, we find that they often produce gestures that convey information that is different from the information conveyed in their speech (Church & Goldin-Meadow, 1986; Perry et al., 1988). The example with which we began this article illustrates this point: When asked to explain her belief that the liquid quantities in the two containers were different, the second child we considered focused on the heights of the containers in her speech but on the widths of the containers in her gestures. Thus, the gesture–speech mismatches that children produce when asked to explain their solutions to a problem provide clear evidence that children can, and do, entertain a variety of strategies or solutions on the same problem. In the next section, we examine whether the within-problem variability evident in gesture–speech mismatch is associated with periods of transition, as we might expect if it functions as an impetus for change.

B. Gesture–Speech Mismatch and Transition

1. *Gesture–Speech Mismatch Predicts Openness to Instruction*

a. Gesture–Speech Mismatch in Conservation In our previous work, we have observed and explored gesture–speech mismatch in two concepts, mastered at two different ages. The first is an understanding of conservation, as measured by a series of Piagetian conservation tasks (two number tasks, two liquid quantity tasks, and two length tasks). The child is initially shown two objects that are identical in number, liquid quantity, or length and is asked to verify the equivalence of the two objects. The experimenter then transforms one of the two objects (e.g., spreading the row of checkers out, pouring the water into a differently shaped container, reorienting the stick so it is no longer aligned with the other object) and asks the child whether the transformed object has the same or different amount as the untransformed object. Children younger than 7 years of age typically respond that the transformed object has a "different" amount. The child is then asked to justify his or her judgment (see Church & Goldin-Meadow, 1986, for additional procedural details).

Although many investigators have analyzed the spoken justifications children give for their conservation judgments, few have analyzed—or even explicitly noticed—the gestures that children produce along with their speech. In fact, it turns out that children gesture a great deal when asked to justify their conservation judgments (indeed, even congenitally blind children, who gesture infrequently on other tasks, produce gestures on the conservation task, Iverson & Goldin-Meadow, 1995). The gestures children produce on the conservation task often convey the same information as is conveyed in the speech they accompany. However, as described above, gesture can also be used to convey different information from speech. For example, a child in one study said, "they're different because you spread them out," while moving his index finger between the two rows of checkers, pairing each checker in one row with a checker in the second row. This child focused on the experimenter's actions on the objects in speech but focused on the one-to-one correspondence between the checkers in gesture.

b. Gesture–Speech Mismatch in Mathematical Equivalence The second concept we have explored is an understanding of mathematical equivalence (the notion that one side of an equation represents the same quantity as the other side of the equation), as measured by children's responses to addition problems of the following type: $3 + 4 + 6 = \_ + 6$. The child is first asked to solve the problem (i.e., put a number in the blank) and is then asked to explain how he or she arrived at the solution (see Perry et al., 1988, for procedural details). American children typically master this task by the age of 12. A frequent error that children make when solving these problems incorrectly is to add up all of the numbers in the problem (i.e., the child puts 19 in the blank in the above example). When asked to explain this solution, the child might say, "I added the 3, the 4, the first 6, and the second 6, and got 19," while pointing at each of the four numbers. Such a child is conveying the same procedure (the Add-All procedure) in both gesture and speech. However, children can, and frequently do, convey a different procedure in gesture than they convey in speech—that is, they produce gesture–speech mismatches. For example, in explaining the same problem, a child might say, "I added the 3, the 4, the first 6, and the second 6, and got 19," but indicate only the 3 and the 4 with a two-finger V-shaped point. Such a child is conveying the Add-All procedure in speech, but in gesture is giving special status to the two numbers which, if grouped and added, result in a correct answer to the problem.

c. Training Studies to Determine Whether Gesture–Speech Mismatch Predicts Readiness to Learn We have hypothesized that gesture–speech mismatch is a reliable index of the transitional period. To test this hypothesis, we conducted training studies in each of the two concepts, predicting that the children who produced a large number of gesture–speech mismatches would be most likely to benefit from the instruction we provided. Church and Goldin-Meadow (1986) gave children ages 5 to 8 a pretest in conservation, and Perry et al. (1988) gave children ages 9 to 10 a pretest in mathematical equivalence. In each pretest, the child was asked to solve six problems and to explain his or her solutions to each problem. Only children who failed the pretest, that is, who did not solve the six conservation or addition problems correctly, were included in the study. Children were then provided with instruction in the task and, after the training, were given a posttest designed to assess how much their understanding of the task had improved.

On the basis of the explanations they produced on the pretest, children were divided into two groups: (1) those who produced gesture–speech mismatches in three or more of their six explanations, labeled *discordant,* and (2) those who produced mismatches in fewer than three of their explanations, labeled *concordant.* The question then is how many children in each of these two groups were successful on the posttest. Posttest performance was evaluated relative to each child's pretest; as a result, posttest success reflects improvement in a child's understanding of the task. The results are presented in Figure 1, which displays the proportion of concordant and discordant children who were successful on the posttest in the conservation task (A) and in the mathematical equivalence task (B). In both tasks, the discordant children were significantly more likely to succeed on the posttest than were the concordant children ($\chi^2 = 5.36, df = 1, p \leq .02$ for conservation; $\chi^2 = 4.47, df = 1, p < .025$ for mathematical equivalence). Thus, the children who often exhibited variability within a single response on a task, that is, who often produced gesture–speech mismatches, were more likely to profit from instruction on that task than were the children who exhibited little or no within-response variability.

It is important to note that the children in these studies were indistinguishable when viewed from the perspective of speech; all of the children in both studies produced incorrect spoken justifications. Thus, identifying children who were ready to profit from instruction was possible *only if* the children's gestures, as well as their words, were taken into account (but see Graham & Perry, 1993). In addition, we stress that gesture–speech mismatch should not be taken as a general characteristic of the learner independent of the task. Rather, a learner will produce mismatches on a particular task only when he or she is in a transitional period with respect

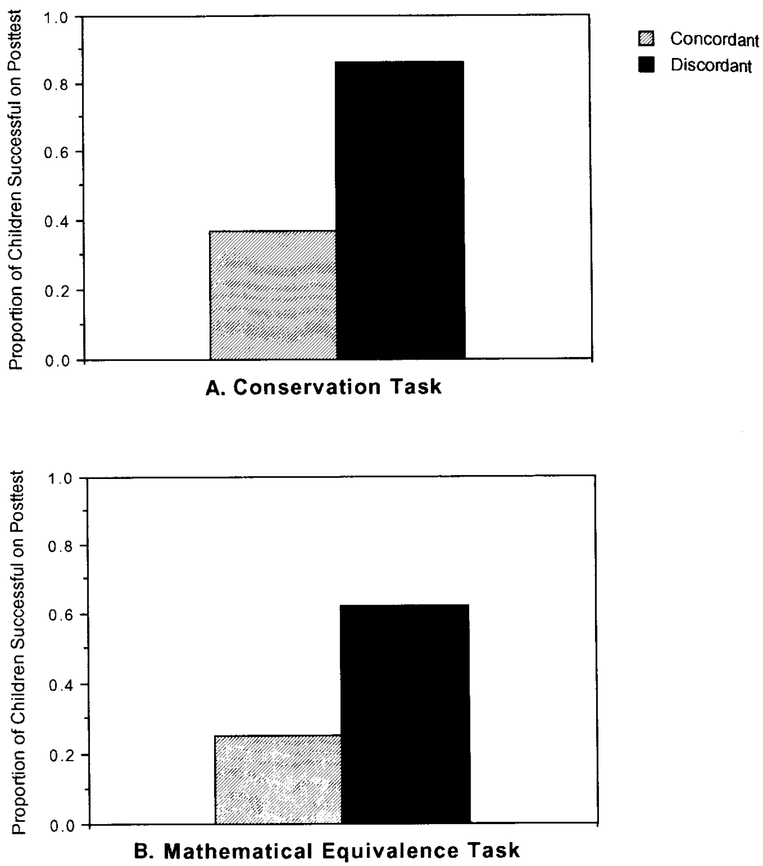


Fig. 1. Success after instruction in concordant versus discordant children. The figure presents the proportion of concordant (hatched bar) versus discordant (solid bar) children who improved their performance after instruction and were successful on a posttest on the conservation task (A) or the mathematical equivalence task (B). In both tasks, the discordant children were significantly more likely to improve their performance and succeed on the posttest than were the concordant children. (A is adapted from Church & Goldin-Meadow, 1986, and B is adapted from Perry, Church, & Goldin-Meadow, 1988.)

to that task. Thus, the same child might well be expected to be concordant on one task and discordant on another, as we have found is often the case (Perry et al., 1988).

2. *Gesture–Speech Mismatch is Preceded and Followed by a Stable State*

We have shown that the discordant state in which children produce a large number of gesture–speech mismatches is transitional in the sense that it is a state in which change is likely. There is, however, another sense in which the discordant state might be expected to be transitional. If the discordant state indexes the transitional period, it ought to be both preceded and followed by a more stable, concordant state. Thus, children might be expected to begin learning about a task in a state in which they produce gesture–speech matches containing incorrect explanations, that is, a concordant incorrect state. They should then progress to a state in which they produce gesture–speech mismatches (which may themselves contain either correct or incorrect explanations), that is, a discordant state. Finally, they should return to a state in which they again produce gesture–speech matches, but matches that contain correct explanations, that is, a concordant correct state.

To test this prediction, Alibali and Goldin-Meadow (1993) conducted a microgenetic study of children's acquisition of mathematical equivalence. They gave 9- and 10-year-old children instruction in mathematical equivalence and observed the children's explanations of the problems they solved over the course of the pretest and training period. The relationship between gesture and speech in each explanation was monitored over the series of problems for children who gestured during the study. Of the 35 children who improved their understanding of mathematical equivalence over the course of the study, 29 (83%) followed the predicted path ($p < .001$, Binomial Test)—11 progressed from a concordant incorrect state to a discordant state, 15 progressed from a discordant state to a concordant correct state, and 3 traversed the entire path, moving from a concordant incorrect state through a discordant state and ending in a concordant correct state. Moreover, the few children who violated the path, moving directly from a concordant incorrect state to a concordant correct state without passing through a discordant state, appeared to have made only superficial progress on the task: They performed significantly less well on a posttest than the children who progressed through a discordant state.

Thus, the discordant state appears to be transitional in that it both predicts openness to instruction and is sandwiched between two relatively stable states. These findings suggest that the within-problem variability evident in gesture–speech mismatch is indeed associated with periods of transition.

C. Gesture–Speech Mismatch Reflects the Activation of Two Ideas in Solving, as Well as Explaining, a Problem

We have established that gesture–speech mismatch is associated with transitional periods. But does mismatch tell us anything about what makes a state transitional? Gesture–speech mismatch, by definition, reflects two different pieces of information within a single response, one conveyed in speech and another conveyed in gesture. As mentioned above, what we take to be significant about mismatch is that it provides evidence, not just that the speaker has two ideas available within his or her repertoire, but that the speaker has invoked both of those ideas on a single problem. The concurrent activation of two ideas on a single problem is what we suggest may be a defining feature of the transitional period.

Note, however, that gesture–speech mismatch is found in explanations, and explanations are produced after a problem is solved and may have little to do with how the problem actually was solved (see Ericsson & Simon, 1980, and Nisbett & Wilson, 1977, for discussions of this issue). Thus, the fact that children exhibit two ideas when *explaining* how they solved a problem does not necessarily mean that the children consider both ideas when actually *solving* the problem. Discordance could reflect post hoc reasoning processes rather than on-line problem solving. To explore this possibility, Goldin-Meadow, Nusbaum, Garber, & Church (1993) conducted a study to determine whether discordant children activate more than one idea, not only when they explain their solutions to a problem, but also when they solve the problem itself. The approach underlying the study assumes that activating more than one idea when solving a problem takes more cognitive effort than activating a single idea. Thus, a child who activates more than one idea on one task should have less capacity left over to simultaneously perform a second task than a child who activates only a single idea.

The concordant and discordant children in our mathematical equivalence studies all solved the addition problems incorrectly. If explanations are an accurate reflection of the processes that take place in problem solving, we would expect the discordant children, who tend to produce two ideas on each explanation (one in speech and a second in gesture), to also activate two ideas when solving each addition problem. In contrast, concordant children, who tend to produce a single idea per explanation, would be expected to activate only one idea when solving each addition problem. If this is the case, the discordant children are, in a sense, working harder to arrive at their incorrect solutions to the addition problems than are the concordant children, and should have less cognitive effort left over to tackle another task.

Goldin-Meadow, Nusbaum, Garber, and Church (1993) tested these predictions in a two-part study. In the first part, children were given six addition problems and asked to solve and then explain the solution to each problem. These explanations were later used to divide children into discordant and concordant groups, as described above. The second part of the study contained a primary math task and a secondary word recall task. On each of 24 trials, children were first given a list of words that they were told they would be asked to remember. They were then given a math problem that they were asked to solve but *not* explain. Finally, the children were asked to recall the word list. It is important to note that the children were not asked for explanations at any time during this second part of the study, and that the primary and secondary tasks were conducted concurrently, thus presumably *both* drawing upon the limited pool of cognitive effort a child has available.

The math task contained two types of problems: Hard math problems that were identical to those used in our previous studies, except that all four numbers in the problem were different (e.g., $3 + 6 + 7 = \_ + 8$), and Easy math problems that also contained four distinct numbers, but all four were on the left side of the equal sign, (e.g., $4 + 7 + 3 + 5 = \_$). The Easy math problems were included as a control because children of this age typically solve problems of this type correctly and produce gesture–speech matches (i.e., single idea explanations) to explain these correct solutions. The word recall task contained two types of lists: one-word lists that were not expected to tax the children's cognitive capacities, and three-word lists that might be expected to strain the children's capacities, particularly if those capacities were already taxed by activating two ideas on a single problem. Thus, each child received six problems of each of four types: a one-word list with an Easy math problem, a three-word list with an Easy math problem, a one-word list with a Hard math problem, and a three-word list with a Hard math problem.

Figure 2A presents the proportion of math problems the children solved correctly on the primary math task. Not surprisingly, none of the children solved the Hard math problems successfully, and almost all of the children solved the Easy problems successfully. Performance on the math task was not affected by the number of words the children had to recall, nor was it affected by whether the child was concordant or discordant in his or her pretest explanations. Thus, the concordant and discordant children performed the same on the math task in terms of number of problems solved correctly. However, we suggest that this identical performance is deceptive and conceals differences in how the two groups of children actually solved the math problems. On the basis of the explanations they produced on the pretest, the discordant children might be expected to activate two ideas

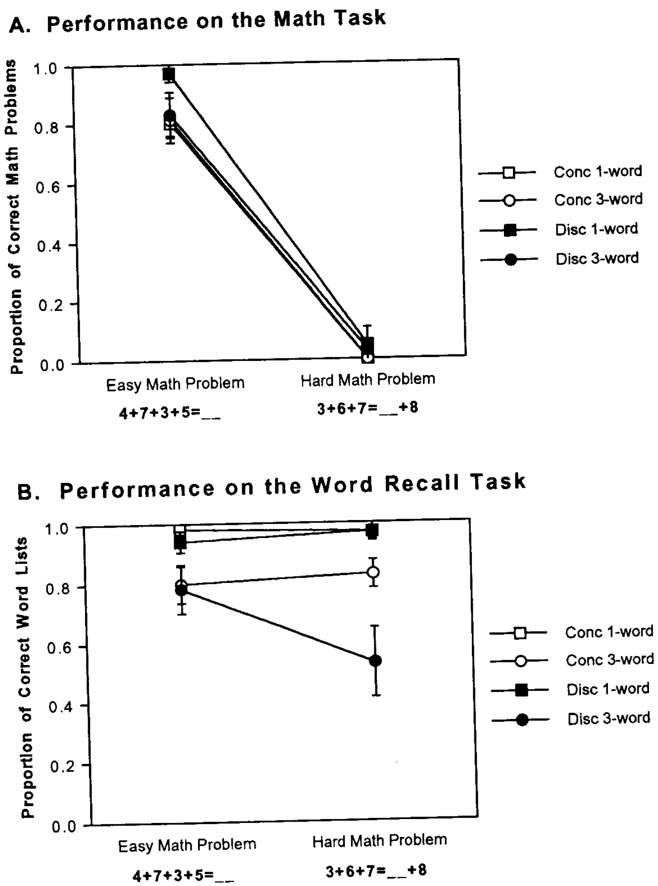


Fig. 2. Performance on the mathematical equivalence addition problems and a concurrently administered word recall task. (A) presents the proportion of Easy and Hard *math problems* solved correctly by concordant (Conc) and discordant (Disc) children under conditions of low (one-word list) and high (three-word list) cognitive load. The children did not differ in their performance on the math problems, either as a function of concordant versus discordant status or as a function of low versus high cognitive load. (B) presents the proportion of *word lists* given with Easy and Hard math problems that were recalled correctly by concordant and discordant children under conditions of low (one-word list) and high (three-word list) cognitive load. After solving the Hard math problems, the discordant children had significantly less capacity available to recall the word lists under conditions of high cognitive load (i.e., on three-word lists) than the concordant children. These data suggest that the discordant children were working harder to arrive at their incorrect solutions to the Hard math problems than were the concordant children. This greater effort is hypothesized to be an outgrowth of the fact that the discordant children activated two ideas when attempting to solve each Hard math problem. The bars reflect standard errors. (Reprinted from Goldin-Meadow, Nusbaum, Garber, & Church, 1993.) Copyright 1993 by the American Psychological Association. Reprinted by permission.

when solving each Hard math problem and thus to be working harder to achieve their incorrect solutions on these problems than the concordant children, who, on the basis of their pretest explanations, are expected to activate only one idea per problem. We turn to the secondary word recall task to provide a gauge of how much effort the children in the two groups expended on the primary math task.

Figure 2B presents the proportion of word lists the children recalled correctly on the secondary task. Consider first performance on the word lists given along with Easy math problems. Both concordant and discordant children were expected to activate a single idea per problem when solving the Easy math problems. Thus, the children should expend the same amount of effort on these math problems and should not differ in the amount of effort left over for word recall. The two groups therefore should recall the same proportion of word lists after solving the Easy math problems—as, in fact, they did. Not surprisingly, both concordant and discordant children recalled a higher proportion of one-word lists than three-word lists after solving the Easy math problems.

We turn next to the word lists recalled after solving the Hard problems, focusing first on the concordant children. On the basis of their pretest explanations, the concordant children were expected to activate a single idea when solving a Hard math problem. Thus, their performance on the word recall task should not differ for lists recalled after solving the Hard problems and for lists recalled after solving the Easy problems. The results presented in Figure 2B confirm this prediction. In contrast, the discordant children, on the basis of their pretest explanations, were expected to activate two ideas when solving a Hard math problem and to expend more effort on this task than the concordant children. They should consequently have less effort left over to expend on recalling the words after solving a Hard math problem and should perform poorly on this task, particularly when their capacities are taxed (i.e., when they are asked to recall the three-word lists). The data displayed in Figure 2B confirm that the discordant children recalled significantly fewer three-word lists after solving the Hard math problems than did the concordant children ($F(1, 15) = 16.477$, $p < .001$).

The data in Figure 2B suggest that the discordant children were working harder than the concordant children to solve the Hard math problems. We suggest, on the basis of their pretest explanations, that the discordant children were working harder on problems of this type because, on each problem, they activated two ideas when attempting to solve the problem. Intuitively, a child in transition ought to be more advanced and should perform better than the child who has not yet entered the transitional period. However, the data in Figure 2B suggest otherwise—the discordant children, who were shown to be particularly ready to learn in previous studies, performed *less well* on the word recall task than the concordant children. When solving the Hard math problems, the discordant children carry the extra burden of too many unintegrated ideas, a burden that appears to take cognitive effort, leaving less effort available for other tasks.

These findings suggest that there may be a cost to being in transition, a cost that may explain why the transitional state is an unstable state. The extra burden carried by the child in transition may make it difficult to remain in a transitional state for long periods. A child in transition who receives good instructional input is likely to progress forward (Alibali & Goldin-Meadow, 1993; Church & Goldin-Meadow, 1986; Perry et al., 1988), but one who does not receive input may find it difficult or costly to maintain transitional status and may regress (Church, 1990). The fact that being in a transitional state demands additional psychological effort may explain why regression to a prior state is commonly observed in learning.

II. The Sources of Gesture–Speech Mismatch

We have suggested that gesture–speech mismatch provides a good index of transition because it reflects a fundamental property of the transitional state. Mismatch reflects the fact that the speaker is activating two ideas on a single problem—a characteristic we take to be central to being in transition. If gesture–speech mismatch is an important characteristic of the transitional state, the factors that create mismatch may be the same factors that render a learner transitional. Thus, our next step is to examine how gesture–speech mismatch comes about.

A. Inferring the Learner's Knowledge Base from Gesture and Speech

We begin by using the explanations a child produces over a set of problems as a basis for inferring what the child knows about the problem. In our studies, a child is asked to solve a problem and then explain that solution.

The child describes a procedure for arriving at a solution and from this procedure we make inferences about the child's understanding of the problem. For example, we assume that children who say they solved the math problem $3 + 6 + 7 = \_ + 7$ by "adding the 3, the 6, the 7, and the 7" have a representation of the problem that includes all four numbers, with no meaningful subgroupings within the numbers (an Add-All procedure). In contrast, children who say they solved the same problem "by adding the 3, the 6, and the 7" are assumed to have a representation of the problem that includes only those numbers on the left side of the equal sign (an Add-to-Equal-Sign procedure). Thus, the procedures the child describes provide insight into the way in which that child represents the problem.

Note that by observing both gesture and speech, we have two different access routes to the child's representation: one through the procedures that the child articulates in speech and a second through the procedures that the child describes in gesture. In concordant children, the two access routes provide evidence for the same representation because, by definition, concordant children tend to produce in gesture the same procedures that they produce in speech. Thus, rarely does a concordant child produce a procedure in speech that the same child does not also produce in gesture. In other words, the *repertoire* of procedures that the concordant child has tends to be produced in both gesture and speech.[1]

Table I presents an example of the six explanations produced by a child who would be considered concordant in our math studies. The child produced five explanations in which the procedure expressed in speech was the same as the procedure expressed in gesture (that is, five matching explanations) and one explanation in which the procedures expressed in the two modalities were different (that is, one mismatching explanation). In three of the matching explanations, Add-All (AA) was the procedure expressed in both modalities; in the remaining two, Add-to-Equal-Sign (AE) was the procedure expressed in both modalities. In the single mismatching explanation, AA was expressed in speech but AE was expressed in gesture. The bottom of the table presents the repertoires of procedures

[1] Our data show that if a concordant child produces gestures on the mathematical equivalence task, the child is likely to produce all of the procedures he or she has available in both gesture and speech. As described in the text, this does not mean that the child produces a gestural equivalent for a spoken procedure on every explanation, or even that the child produces a gestural response on every explanation—only that the child produces a gestural equivalent for each spoken procedure on at least one explanation. It is important to point out, however, that some children (albeit a relatively small proportion) do not gesture at all when explaining their solutions to the mathematical equivalence task. These children obviously must produce all of their procedures in speech and none in gesture. Data from nongesturers have not been included in the repertoire analyses presented here, but see Alibali and Goldin-Meadow (1993) for further discussion and description of children who do not gesture on the math task.

TABLE I

EXPLANATIONS AND REPERTOIRES OF A CONCORDANT CHILD ON SIX MATH PROBLEMS

	Explanations		
Problem number	Relationship between speech and gesture	Procedure expressed in speech	Procedure expressed in gesture
1	Match	AA[a]	AA
2	Match	AA	AA
3	Match	AA	AA
4	Match	AE[b]	AE
5	Match	AE	AE
6	Mismatch	AA	AE

The repertoires inferred from this set of six problems

Type of repertoire	Procedures expressed in the repertoire
Gesture and speech	AA, AE
Speech only	None
Gesture only	None

[a] AA, the Add-All procedure.
[b] AE, the Add-to-Equal-Sign procedure.

that we would infer from this set of responses. The child expressed two procedures in both gesture and speech (AA and AE), and no procedures in speech alone or gesture alone. Note that the child's repertoires are based on whether a procedure ever appears in a given modality over the set of six responses. Thus, a procedure did not have to be expressed in gesture and speech on the same problem to be considered part of the Gesture and Speech repertoire; it had only to appear sometime in gesture and sometime in speech. Conversely, a procedure that is expressed in gesture alone on a single problem (e.g., the AE procedure in problem 6 in Table I) is not necessarily part of the child's Gesture Only repertoire; it would qualify as a part of this repertoire only if it were *never* produced in speech on any of the six explanations. In general, concordant children, by definition, tend to have repertoires in which all of the procedures they produce are part of a Gesture and Speech repertoire, with very few, if any, procedures in either the Gesture Only or the Speech Only repertoires.

In contrast to concordant children, in discordant children, the two access routes provided by speech and gesture offer evidence for two different

representations: one expressed in speech and a second expressed in gesture. Thus, discordant children appear to be working with two different representations of the same problem. What types of repertoires does the discordant child then have? In fact, there are two different types of repertoires that a child could have and still be discordant. Table II presents two possible sets of explanations that, in principle, a child could produce and be considered discordant. Note that the two sets result in different repertoires.

In response pattern #1, the child produces two matching explanations and four mismatching explanations. AA is expressed in both speech and gesture in the matching explanations (problems 1 and 2). AA is also expressed in speech in two of the mismatching explanations (problems 3 and 4), and is expressed in gesture in the two other mismatching explanations (problems 5 and 6). AE is expressed in speech in two of the mismatching explanations (problems 5 and 6), and is expressed in gesture in the two other mismatching explanations (problems 3 and 4). Thus, AA belongs to

TABLE II

POSSIBLE EXPLANATIONS AND REPERTOIRES FOR A DISCORDANT CHILD

		Possible sets of explanations			
		Response pattern #1		Response pattern #2	
Problem number	Relationship between speech and gesture	Procedure expressed in speech	Procedure expressed in gesture	Procedure expressed in speech	Procedure expressed in gesture
1	Match	AA[a]	AA	AA	AA
2	Match	AA	AA	AA	AA
3	Mismatch	AA	AE[b]	AA	AE
4	Mismatch	AA	AE	AA	AE
5	Mismatch	AE	AA	AA	AE
6	Mismatch	AE	AA	AA	AE

The repertoires inferred from the two possible sets of explanations

Type of repertoire	Procedures expressed in the repertoire for response pattern #1	Procedures expressed in the repertoire for response pattern #2
Gesture and speech	AA, AE	AA
Speech only	None	None
Gesture only	None	AE

Note: Note that Response Pattern #1 results in an overall repertoire comparable to the concordant child's overall repertoire, whereas Response Pattern #2 results in an overall repertoire that differs from the concordant child's overall repertoire.
[a] AA, = the Add-All procedure.
[b] AE = the Add-to-Equal-Sign procedure.

the Gesture and Speech repertoire, as does AE; there are no procedures in the Speech Only or the Gesture Only repertoires. Note that a child who produces response pattern #1, although discordant, has precisely the same overall set of repertoires as the concordant child in Table I.

We now turn to response pattern #2 in Table II. Here the child again produces two matching and four mismatching explanations. AA is again expressed in speech and gesture in the matching explanations (problems 1 and 2). In addition, AA is expressed in speech in all four mismatching explanations (problems 3–6). Note, however, that AE is not expressed in speech anywhere in this set of six responses; it appears in gesture in all four mismatching explanations (problems 3–6). Thus, AA belongs to the Gesture and Speech repertoire but AE belongs to the Gesture Only repertoire; again there are no procedures in the Speech Only repertoire.

The hypothetical response patterns displayed in Table II make it clear that there are two ways in which a child can be discordant. One way is associated with a set of repertoires that is identical to the set a concordant child has, but the second way is associated with a set of repertoires that is decidedly different from the concordant child's set. If concordant and discordant children differ only in the response patterns they exhibit and not in their repertoires, then this suggests that the knowledge the two types of children have about the task is identical—the children differ only in how they activate that knowledge on a given problem. Concordant children tend to activate one procedure on each problem (expressed in both speech and gesture), whereas discordant children tend to activate two procedures (one in speech and another in gesture). But overall the children have the same number of procedures in their sets of repertoires, and all of those procedures are expressed in both modalities and, at some time, appear in speech and in gesture.

In contrast, if concordant and discordant children differ not only in their response patterns but also in their repertoires, the knowledge the two types of children have about the task may not be identical. Differences in a child's knowledge base may ultimately be responsible for creating a discordant response pattern and may, in the end, be what makes a child transitional. We address this issue by examining the types of repertoires that concordant and discordant children actually produce.

B. The Gesture and Speech Repertoires Produced by Concordant and Discordant Children

We examined the repertoires of responses produced before instruction by each of the 58 children who gestured on the pretest problems in Alibali and Goldin-Meadow's (1993) study. There were 35 discordant children and 23 concordant children in this group (see Goldin-Meadow, Alibali & Church, 1993, for the details of this analysis). Figure 3 presents the mean number of different procedures that the concordant and discordant children produced in their Gesture and Speech repertoires (A), their Speech Only repertoires (B), and their Gesture Only repertoires (C). As is apparent in the figure, the concordant and discordant children did *not* have the same sets of repertoires. The discordant children produced significantly more procedures in their Gesture Only repertoires than did the concordant children ($F\,(1{,}56) = 36.34$, $p < .001$). Interestingly, the two groups of children did not differ in the number of procedures they produced in their Gesture and Speech repertoires ($F\,(1{,}56) = 1.802$, $p > .10$), nor in the number of procedures they produced in their Speech Only repertoires ($F\,(1{,}56) = 2.28$, $p > .10$). Note that both groups of children produced very few procedures in speech without, at some time, also producing those procedures in gesture.

If the number of procedures found in the Gesture and Speech and in the Speech Only repertoires is the same for the discordant and concordant children, and if the discordant children have more procedures in their Gesture Only repertoires than the concordant children, then the discordant children must have *more* procedures in their repertoires overall than do the concordant children. That is, the discordant children have more procedures potentially available to them than the concordant children—they have larger knowledge bases. However, virtually all of the additional procedures that the discordant children have in their repertoires are procedures that the children express in gesture but do not (and perhaps cannot) express in speech.

If a large number of procedures in the Gesture Only repertoires is essential to the discordant state, then we ought to see changes in this repertoire as children move into and out of this state. Alibali and Goldin-Meadow (1993) examined the repertoires of the children who, after receiving instruction, progressed from a concordant incorrect state to a discordant state, and the repertoires of the children who, after instruction, progressed from a discordant state to a concordant correct state. The data are presented in Figure 4; note that this analysis is within-child (i.e., the same child in a concordant state at one time vs. a discordant state at another time) rather than across-child as seen in Figure 3 (i.e., concordant children vs. discordant children). As predicted, the children produced significantly more procedures in their Gesture Only repertoires when they were in a discordant state versus a concordant incorrect state ($t = 3.1$, $df = 11$, $p < .01$, left graph) and in a discordant state versus a concordant correct state ($t = 3.0$, $df = 16$, $p \leq .008$, right graph). Thus, the children *increased* the number of procedures in their Gesture Only repertoires when they moved into a discordant state and *decreased* the number when they moved out of a discordant state. In other words, the children increased the number of

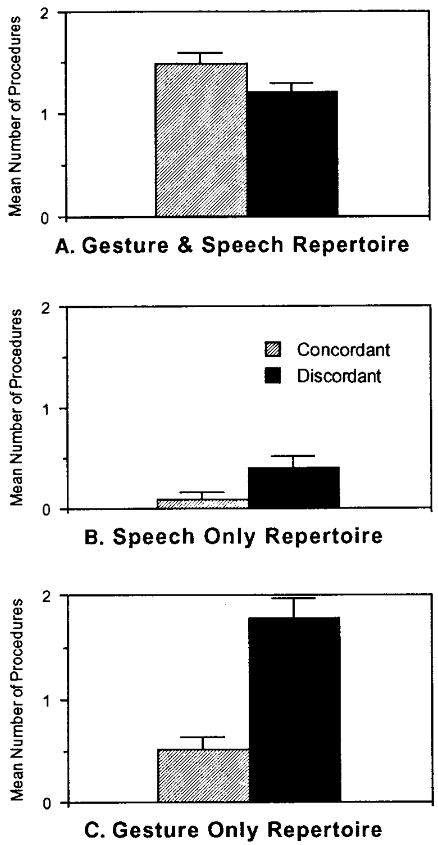


Fig. 3. The repertoires of procedures produced by concordant (hatched bar) versus discordant (solid bar) children in their explanations of mathematical equivalence problems. The figure presents the mean number of different procedures the children in each group demonstrated in their Gesture and Speech repertoires (A), in their Speech Only repertoires (B), and in their Gesture Only repertoires (C). The discordant children had significantly more procedures in their Gesture Only repertoires than did the concordant children, but did not differ from the concordant children in the number of procedures they had in their Gesture and Speech and Speech Only repertoires. The concordant and discordant children thus differed only in the number of different procedures they expressed uniquely in gesture. The bars reflect standard errors. (Adapted from Goldin-Meadow, Alibali, & Church, 1993.)

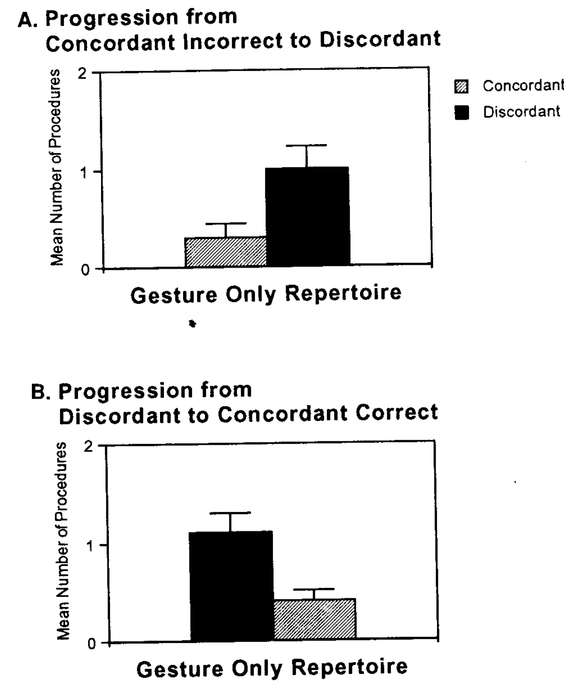


Fig. 4. The Gesture Only repertoires children produce as they progress from one state to another in the acquisition of mathematical equivalence. The figure presents the mean number of different procedures children demonstrated in their Gesture Only repertoires as they progressed from the concordant (hatched bar) incorrect state to the discordant (solid bar) state (A) and as they progressed from the discordant state to the concordant correct state (B). The children significantly increased the number of procedures they expressed uniquely in gesture when they entered a discordant state, and significantly decreased the number when they exited the state. The bars reflect standard errors. (Adapted from Alibali & Goldin-Meadow, 1993.)

procedures they expressed *uniquely* in gesture when they entered a transitional state and decreased the number when they exited the state. These findings suggest that having a large number of procedures unique to gesture may be an important aspect of being in transition, and that the "experimentation" with new procedures that may occur during the transitional period is likely to be expressed in gesture rather than in speech.

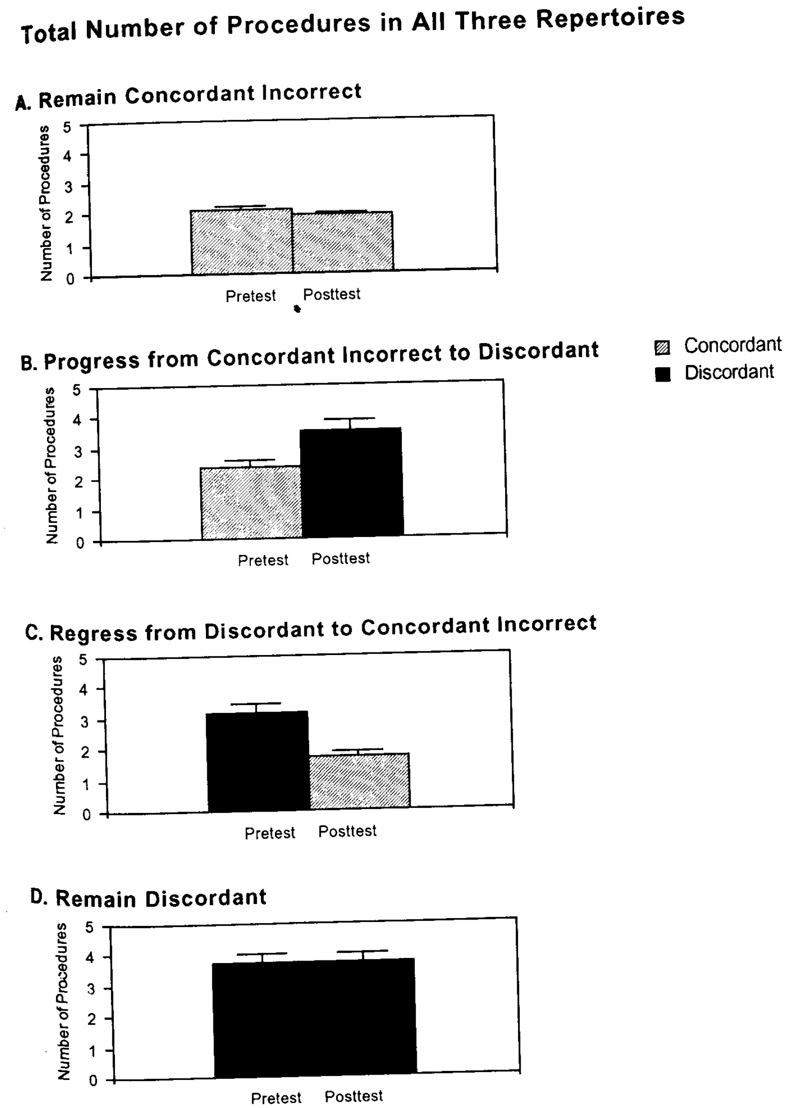
C. The Processes by Which Repertoires Change

We have found that the size of a child's repertoire of procedures, that is, the number of different procedures the child has available to deal with a task, changes as the child moves in and out of transition with respect to that task. However, it is worth noting that, at all points in the acquisition process, children tend to have at their disposal more than one procedure (cf. Fig. 3). Even the concordant children in the Alibali and Goldin-Meadow (1993) study had more than one procedure in their repertoires overall (Mean = 2.09 procedures, SD = 0.85, summing across all three repertoires, compared to 3.37, SD = 1.24, for the discordant children). Thus, children exhibit variability throughout the acquisition process, more variability than one might expect if learning were to involve moving from one consistent state to another.

We turn now to the question of how a child's repertoire might change. A model in which a learner moves from one consistent state to another would predict that the learner abandons the procedure he or she has at time 1, replacing it with a completely different procedure at time 2. Under this view, very little of the learner's repertoire would be maintained over time, and change would be accomplished primarily by abandoning old procedures and generating new ones.

Alibali (1994) explored this issue in a training study in mathematical equivalence. Alibali's goal in this study was to provide children with minimal instruction, designed to encourage children to change their understanding of the task but not necessarily to master the task. And, indeed, as intended, the children in the study made small amounts of progress, some progressing not at all, thus allowing Alibali to examine the initial steps children take as they begin to tackle mathematical equivalence. The study involved four groups of children, three who received some type of instruction in mathematical equivalence and one control group. Of the children who received instruction, 35 began the study in a concordant incorrect state and stayed there, 14 began in a concordant incorrect state and progressed to a

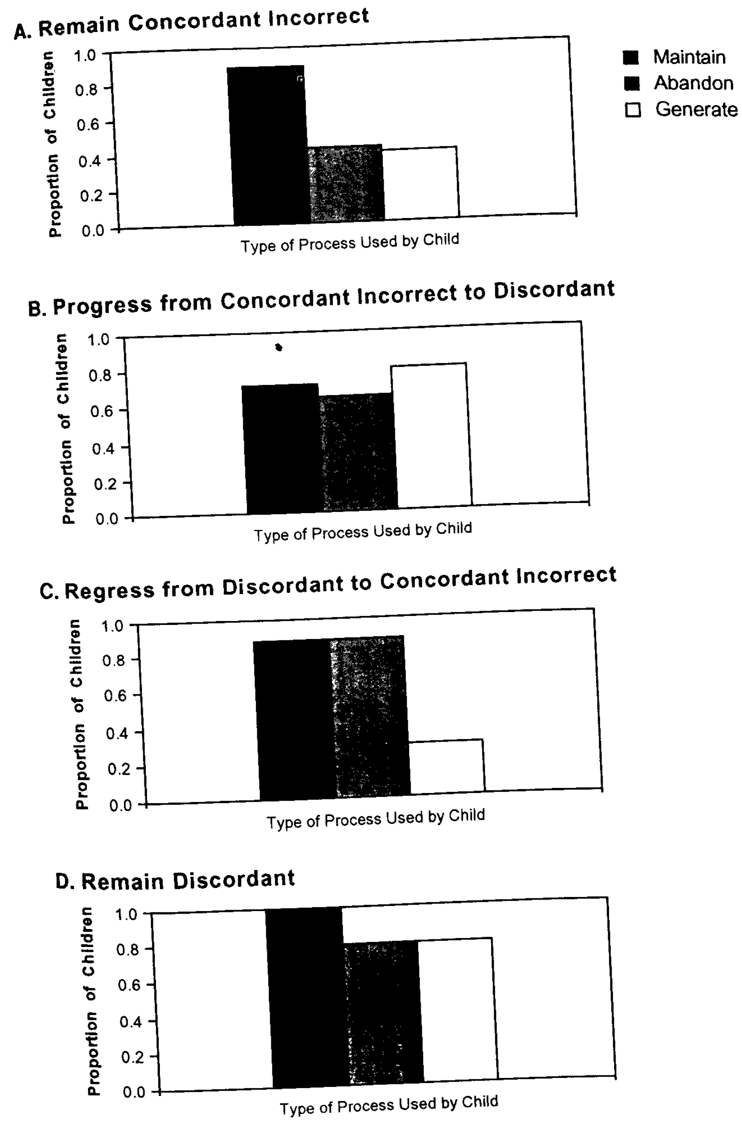
Fig. 5. The total repertoires children produce before and after minimal instruction in mathematical equivalence. The figure presents the mean number of different procedures children produced in all three repertoires (i.e., in their Gesture and Speech, Speech Only, and Gesture Only repertoires combined) when they remained in the concordant (hatched bar) incorrect state (A), when they progressed from the concordant incorrect state to the discordant (solid bar) state (B), when they regressed from the discordant state to the concordant incorrect state (C), and when they remained in the discordant state (D). The children produced larger repertoires (i.e., more different procedures were available to them) when in a discordant state than when in a concordant state. The bars reflect standard errors.



discordant state, 17 began in a discordant state and regressed to a concordant incorrect state, and 14 began in a discordant state and stayed there. Our first step was to confirm in this new data set that children produce more different types of procedures in their repertoires overall when in a discordant state than when in a concordant state. Figure 5 presents the data. Children who remained in the state in which they began the study did not significantly increase or decrease the number of procedures they had in their overall repertoires ($t = .927$, $df = 34$, n.s., for the children who remained in a concordant incorrect state; $t = 0$, $df = 13$, n.s., for the children who remained in a discordant state). The children who remained in a concordant state throughout the study had approximately two procedures in their overall repertoires both before and after training, and the children who remained in a discordant state throughout the study had close to four procedures in their overall repertoires both before and after training. In contrast, and as predicted, children who progressed from a concordant incorrect state to a discordant state significantly increased the number of procedures in their overall repertoires as they entered the discordant state ($t = 2.74$, $df = 13$, $p < .02$), and children who regressed from a discordant state to a concordant incorrect state significantly decreased the number of procedures in their overall repertoires as they left the discordant state ($t = 4.15$, $df = 16$, $p \leq .001$).

Alibali (1994) then compared the particular procedures that comprised each child's overall repertoire before and after instruction (i.e., on the pretest and posttest) and determined whether each procedure was present in the pretest repertoire and *maintained* to the posttest repertoire, present in the pretest repertoire and *abandoned* in the posttest repertoire, or absent in the pretest repertoire and *generated* in the posttest repertoire. Figure 6 presents the proportion of children who maintained at least one procedure

Fig. 6. The proportion of children who maintained (solid bar), abandoned (shaded bar), and generated (white bar) procedures after minimal instruction in mathematical equivalence. The figure presents the proportion of children who maintained at least one procedure from the pretest to the posttest, the proportion who abandoned at least one procedure, and the proportion who generated at least one procedure. The children are categorized according to the states they were in before and after instruction: Children who remained in the concordant incorrect state (A), children who progressed from the concordant incorrect state to the discordant state (B), children who regressed from the discordant state to the concordant incorrect state (C), and children who remained in the discordant state (D). Virtually all of the children maintained at least one procedure from the pretest to the posttest regardless of the type of transition they made. In addition, whereas the concordant incorrect children remained in that state by keeping their repertoires intact (maintaining procedures rather than abandoning or generating them), the discordant children maintained their status by revamping their repertoires (maintaining, abandoning, and generating procedures).



over the course of the study, the proportion who abandoned at least one procedure, and the proportion who generated at least one procedure. Children could, and frequently did, exhibit all three processes. The data in Fig. 6 are categorized according to the type of transition the child made during the study (remained concordant incorrect, progressed from concordant incorrect to discordant, regressed from discordant to concordant incorrect, and remained discordant). Note first that, independent of the type of transition the child made, the children were very likely to maintain at least one procedure from the pretest to the posttest; across all four types of transitions, 88% of the 80 children maintained at least part of their repertoires. Thus, children were not replacing the repertoires they had at time 1 with a completely new repertoire at time 2.

Perhaps not surprisingly, children who remained concordant incorrect throughout the study tended to keep their repertoires intact—almost all of the children maintained at least one procedure (but not more than two procedures, cf. Fig. 5), and relatively few abandoned old procedures or generated new ones. In contrast, the children who began the study concordant incorrect and progressed to a discordant state exhibited all three processes—they maintained some of their old procedures, abandoned other old procedures, and generated new procedures, as one might expect given that they enlarged their repertoires over the course of the study.

The children who began the study in a discordant state and regressed to a concordant incorrect state maintained some old procedures and abandoned others, but very few generated new procedures—again as one might expect because these children shrank their repertoires over the course of the study. The surprising data came from the children who remained discordant throughout the study. Unlike the children who remained concordant incorrect and maintained their status over the course of the study by keeping their repertoires intact, the discordant children maintained their status by totally revamping their repertoires—they maintained some old procedures, abandoned others, and generated new procedures, keeping the total number of procedures the same (and high, see Fig. 5) but changing the particular procedures. Despite the fact that these children did not make overt progress during the study, they obviously had been working on the task and might well have progressed to a concordant correct state if they had been given adequate instruction.

In sum, children appear to maintain a great deal of continuity when learning a new task, retaining some old procedures for dealing with the task even as they acquire new ones. Continuity of this sort suggests that the transitions children make as they learn a task are gradual rather than abrupt. Children do not appear to change abruptly from a state in which they entertain a single approach to a problem to a state in which they entertain a completely new approach to that problem. Rather, they maintain a variety of approaches to the problem throughout acquisition, gradually increasing that variety as they enter a transitional state and decreasing it as they emerge from the transitional state. Importantly, most of the increased variety that a child exhibits when in the transitional state can be found in the procedures the child expresses uniquely in gesture (i.e., the procedures the child produces in gesture and not in speech), highlighting once again that the transitional state may be difficult to detect if all one does is listen.

III. The Role of Gesture–Speech Mismatch in the Learning Process

We have shown that gesture–speech mismatch in the explanations a child produces when explaining a task is a reliable indicator that the child is in transition with respect to that task. Thus, the mismatch between gesture and speech can serve as an index that experimenters may use to identify and characterize children in transition. In this section, we explore whether gesture–speech mismatch has significance, not only for the experimenter, but also for the learner. In other words, what role (if any) does gesture–speech mismatch play in the mechanism of cognitive change?

A. The Effects of Gesture–Speech Mismatch on the Learner

Our findings suggest that children in transition with respect to a task will tend to produce gesture–speech mismatches when they explain that task. We have further suggested that mismatch comes about because children in transition possess information that they can express in gesture but do not express in speech. If this information is to be conveyed, it must inevitably be produced in a mismatch because there is no match for this particular gesture in the child's speech repertoire. Mismatch thus provides an excellent vehicle for identifying children who have more knowledge at their disposal than is evident in their speech. The nature of this knowledge base may, in fact, be what makes a child transitional. However, it is also possible that the production of mismatches may be important to transition. Earlier we suggested that expressing two ideas on the same problem might itself provide the impetus for change. The question is whether mismatch merely serves as an excellent device for detecting transition, or whether it plays a role in causing transition as well—that is, is gesture–speech mismatch a marker or a mechanism?

Although we do not yet have an answer to this question, the findings we have presented thus far suggest a way in which the question might be approached. We have shown that discordant children have procedures that they express in gesture but not speech (i.e., they have a Gesture Only repertoire). In addition, discordant children, by definition, produce a large number of mismatches. They thus satisfy both of the features associated with the transitional state. In order to determine whether it is the underlying knowledge base or the production of mismatches itself that is essential to transition, these two features must be pulled apart. To do this, we need a group of children who have a Gesture Only repertoire but produce few gesture–speech mismatches. Fortuitously, concordant children fall naturally into two groups: those who produce some procedures in gesture but not in speech (i.e., who have a Gesture Only repertoire) and those who do not. Note, however, that none of the concordant children, by definition, produces a large number of gesture–speech mismatches.

The result is three groups of children whose progress after instruction can be compared: (1) discordant children who have a Gesture Only repertoire and produce a large number of mismatches, (2) concordant children who have a Gesture Only repertoire and produce few mismatches, and (3) concordant children who do *not* have a Gesture Only repertoire and produce few mismatches.[2] If having a Gesture Only repertoire is all that is essential to the transitional state, then groups 1 and 2 should be more likely to profit from instruction (i.e., do better on the posttest after training) than group 3. Such a finding would suggest that the nature of the knowledge base—in particular, having information in gesture that is not expressed in speech—is what is essential to the transitional state. In contrast, if number of mismatches is the key to transition, then group 1 should do better on the posttest than groups 2 and 3. This finding would suggest that it is the activation of two ideas on the same problem, rather than having a larger repertoire of ideas uniquely encoded in gesture, that is essential to transition. Finally, there is the possibility of an interaction—having a Gesture Only repertoire may be necessary for a child to be in a transitional state, but the production of mismatches may further enhance the child's ability to profit from instruction. If the interaction hypothesis is correct, group 1 should perform better on the posttest than group 2 which, in turn, should perform better than group 3. This outcome would suggest that having a repertoire of ideas uniquely encoded in gesture determines whether a child is in a transitional state, but the activation of those two ideas on the same problem—one in speech and the other in gesture—measurably increases the child's readiness to learn. Our future work will be designed so that these analyses can be performed, thus allowing us to determine whether that act of producing gesture–speech mismatches itself facilitates transition.

[2] Although it is logically possible to have the fourth group—discordant children who do *not* have a Gesture Only repertoire and produce a large number of mismatches (cf., response pattern #1 in Table II)—we have found no children who meet this description in any of our studies thus far.

Even if it turns out that the production of gesture–speech mismatches has little role to play in facilitating cognitive change by affecting the learner directly, it is still possible that mismatch can play an indirect role in cognitive change by exerting an influence on the learning environment. In the next section, we explore the conditions that would have to be met in order for this possibility to be realized.

B. The Effects of Gesture–Speech Mismatch on the Learning Environment

We have shown that gesture–speech mismatch identifies children in a transitional state, that is, children who are ready to learn a particular task. Of course, whether children actually learn the task depends on many factors, not the least of which is the input they receive from the environment (see, for example, Perry, Church, & Goldin-Meadow, 1992). The mismatch between a child's gestures and speech can, in principle, alert a communication partner to the fact that the child is ready to learn and can indicate the areas in which the child is most ready to make progress. Equipped with such information, a communication partner may be able to provide input that is tailored to the child's current needs. Children would then, in a sense, be shaping their own environments, making it more likely that they would receive the type of input they need to progress. The question is, are they? The first step in exploring whether mismatch plays this type of indirect role in cognitive change is to show that gesture is interpretable, even to those who have not been trained to observe and code it.

We investigated whether adults, not trained in coding gesture, used the information conveyed in a child's gestures to assess that child's knowledge of conservation (Goldin-Meadow, Wein, & Chang, 1992) or mathematical equivalence (Alibali, Flevares, & Goldin-Meadow, 1994). The design of the studies was straightforward. We selected from videotapes collected in our previous studies examples of 12 children, all of whom gave incorrect explanations in their speech. The examples were chosen so that 6 of the children produced gestures that matched their spoken incorrect explanations, and 6 produced gestures that did *not* match their spoken incorrect explanations. Adults were asked to view the videotape containing these 12 examples and, after seeing each child, to assess the child's understanding of conservation or mathematical equivalence. The adults' spoken and gestured assessments of each child were evaluated in terms of how faithful they were to the information conveyed in the child's speech. Explanations that the adult attributed to the child but which the child had *not* expressed in speech were called Additions.

Figure 7 presents the proportion of responses containing Additions that the adults produced when they assessed concordant children versus discordant children in the conservation task and the mathematical equivalence task. In both tasks, the adults produced significantly more Additions when assessing discordant children than when assessing concordant children ($t = 4.25$, $df = 19$, $p < .001$ for conservation; $t = 3.15$, $df = 19$, $p < .005$ for mathematical equivalence). Moreover, a large proportion of the Additions produced in each task could be traced to the gestures the child produced. More remarkably, although the children had produced the additional information in gesture, the adults often "translated" this information into words and expressed it in their own speech. For example, a child on the videotape

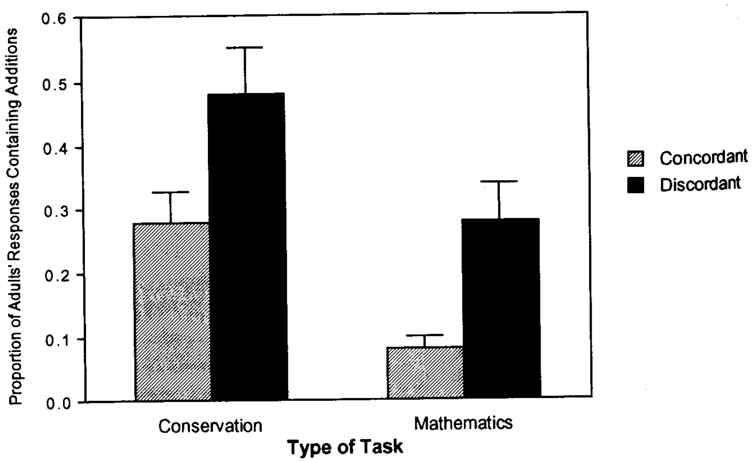
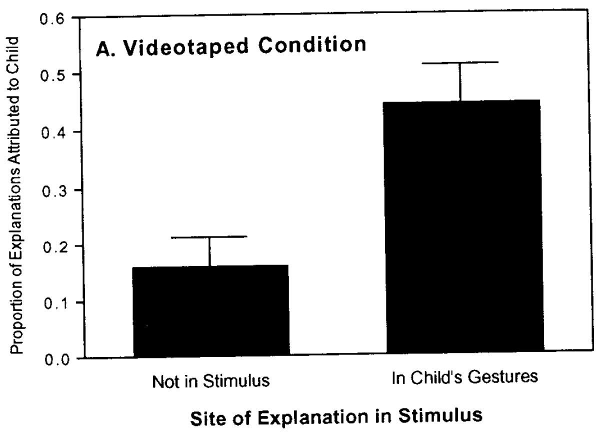


Fig. 7. Adults' spontaneous assessments of concordant (hatched bar) and discordant (solid bar) children's understanding of conservation and mathematical equivalence. The figure presents the proportion of the adults' responses containing Additions (i.e., responses in which the adult added to the information a child conveyed in speech) that were produced when the adults assessed children's understanding of conservation or mathematical equivalence. The children were categorized according to whether their gestures matched (concordant children) or mismatched their speech (discordant children). The adults were significantly more likely to add to the information conveyed in the children's speech when the children were discordant than when they were concordant, suggesting that the adults attended to the children's gestures and considered those gestures in relation to the children's speech. The bars reflect standard errors.

in the conservation study explained his belief that the numbers in the two rows are different by saying "they're different because you spread them out" but gesturing that each of the checkers in one row could be paired with a checker in the other row (one-to-one correspondence). In assessing this child's understanding of the checker problem, one of the adults said, "he thinks they're different because you spread them out, but he sees that the rows are paired up," thereby picking up on the reasoning the child expressed not only in speech but also in gesture. Thus, the adults were able to interpret the information the child conveyed uniquely in gesture and incorporate it into their own spoken assessments of the child.

These findings suggest that adults *can* interpret the gestures a child produces, at least when they are presented on videotape. In an attempt to determine whether adults can interpret children's gestures when they are produced in a naturalistic situation, Momeni (1994) altered the experimental paradigm. Rather than give the adult the open-ended task of assessing each child's understanding of conservation, she gave the adult a list of possible conservation explanations that the child could produce and asked the adult to check off all of the explanations that the child actually did produce. This technique allowed the adult to assess the child's understanding of the task as the task was being administered, a procedure that could be used in a naturalistic context. In addition, giving the adult the same set of explanations for each child allows us to determine how often an explanation will be selected when the child expresses it in gesture only, and compare it to how often the *same* explanation will be selected when the child does not express it at all. In this way, this technique provides us with a baseline for determining how likely a particular explanation is to be attributed to a child, even when it is not expressed by the child.

Momeni (1994) first tried the checklist technique with a videotaped stimulus; she asked 16 adults to view a videotape comparable to the one used in the Goldin-Meadow et al. (1992) study, and to check off the explanations that could be attributed to each child on the tape. She then used the same technique with seven adults asked to observe a series of children as they actually participated in the conservation task. Each adult watched six children, each of whom responded to six conservation tasks. The adult was given a separate checklist for each conservation problem. Figure 8 presents the data for both the videotaped condition (A) and the naturalistic condition (B). The figure displays the proportion of times the adults attributed an explanation to a child when that explanation was produced by the child in gesture only versus not produced by the child at all. In both conditions, the adults were significantly more likely to attribute an explanation to a child when the child expressed it in gesture only than when that same



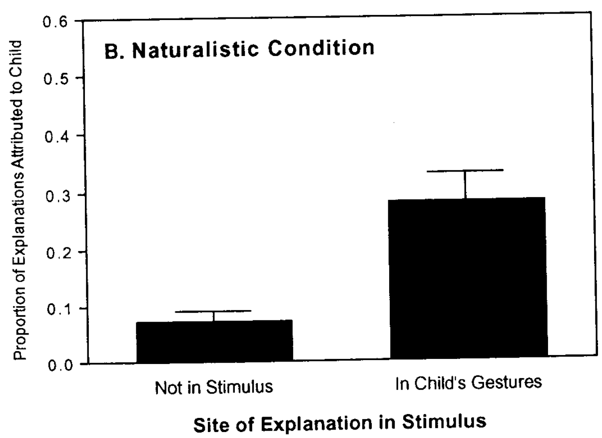


Fig. 8. Adults' responses on a checklist assessing children's understanding of conservation. The figure presents the proportion of times the adults attributed an explanation to a child, that is, the proportion of times the adults responded "yes" to an explanation on a checklist, when that explanation was produced by the child in gesture only (i.e., explanation in Child's Gestures) versus not produced by the child at all (explanation Not in Stimulus). In the Videotaped Condition (A), a videotape of a series of children explaining their conservation judgments was presented to the adults; in the Naturalistic Condition (B), a series of children were observed "live" as they participated in the conservation tasks. Under both conditions,

explanation was not expressed at all ($t = 4.08$, $df = 16$, $p < .01$, for the videotaped condition; $t = 5.17$, $df = 6$, $p < .01$, for the naturalistic condition). Thus, adults are capable of gleaning meaning from a child's gestures even when those gestures are seen once, for a fleeting moment, in a naturalistic context.

These findings suggest that adults can detect and interpret gesture even in a relatively naturalistic situation. Of course, whether adults notice and interpret a child's gestures when they themselves are interacting with a child, and whether adults alter the way in which they interact with a child on the basis of the information they glean from the child's gestures, remain open questions that must be pursued before we can be certain that gesture plays a role in shaping the child's learning environment.

IV. The Representation of Information in Gesture and Speech

A. Verifying the Assumption That Gesture Reflects Knowledge

We have predicated all of the studies discussed thus far on the assumption that gesture is a vehicle through which children can express their knowledge. In this section, we describe empirical evidence that we have collected in support of this assumption. We ask whether the gestures children produce when explaining a problem convey information that can be accessed and recognized in another context. If gesture is a vehicle through which children express their knowledge, then it should be possible to access the knowledge that the children express in gesture via other means.

Garber, Alibali, and Goldin-Meadow (1994) gave 9- and 10-year-old children the standard mathematical equivalence pretest, and used those pretests to determine which procedures the children expressed in their Gesture and Speech repertoires, their Speech Only repertoires, and their Gesture Only repertoires. They then gave each child a judgment test containing 36 math problems. On each problem, the child was presented with a solution generated by one of the six most common procedures children use to solve math problems of this type, and was asked to judge how acceptable that solution is for this problem. For example, for the problem

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the adults were significantly more likely to attribute an explanation to a child when the child expressed it in gesture only than when the child did not express it at all, suggesting that the adults were able to glean accurate information from the children's gestures. The bars reflect standard errors.

3 + 6 + 7 = __ + 7, the child was shown the number 23, a solution arrived at using the Add-All procedure (i.e., adding all four numbers in the problem), and was asked to judge how acceptable 23 is as a solution to this problem. The children were not asked for explanations at any point during the judgment task.

Garber et al. (1994) first examined the children's pretests and identified 20 children whose procedures were all in a Gesture and Speech repertoire (i.e., any procedure the child produced in one modality was also produced at some time in the other modality), and 16 children whose procedures were divided between a Gesture and Speech repertoire and a Gesture Only repertoire (i.e., some procedures were produced in both modalities, whereas others were produced in gesture but not in speech). Not surprisingly given the data in Figure 3, Garber et al. found very few children who had procedures in a Speech Only repertoire, that is, very few children who produced a procedure in speech without also at some point producing it in gesture; the judgment data for these few children will not be discussed here (but see Garber et al., 1994).

Garber et al. then examined the judgment data for the 20 children whose procedures were all in a Gesture and Speech repertoire. They compared the mean acceptability rating for solutions generated by procedures that the children produced in both gesture and speech on the pretest, to the mean acceptability rating for solutions generated by procedures that the children had not produced in either modality on the pretest. They found that the children gave significantly higher ratings to procedures that they produced in both gesture and speech than to procedures that they did not produce at all ($t = 4.17, df = 19, p < .0001$). These results are not surprising, but they do confirm that the acceptability rating has some validity as a measure of a child's knowledge.

We turn now to the data of interest—that is, to the judgment data for the 16 children who had procedures in both a Gesture and Speech repertoire and a Gesture Only repertoire. Figure 9 presents the mean acceptability rating for solutions generated by procedures that these children produced in both gesture and speech on the pretest, the rating for solutions generated by procedures that the children produced in gesture but not speech on the pretest, and the rating for solutions generated by procedures that the children did not produce in either modality on the pretest. The three ratings differed significantly from one another ($F(2, 15) = 23.07, p < .0001$). In particular, the rating for procedures produced in both gesture and speech was significantly higher than the rating for procedures produced in gesture only ($F(1, 15) = 13.83, p < .01$) which, in turn, was significantly higher than the rating for procedures produced in neither modality ($F(1, 15) = 12.08, p < .01$). The latter comparison is of particular interest to us because it

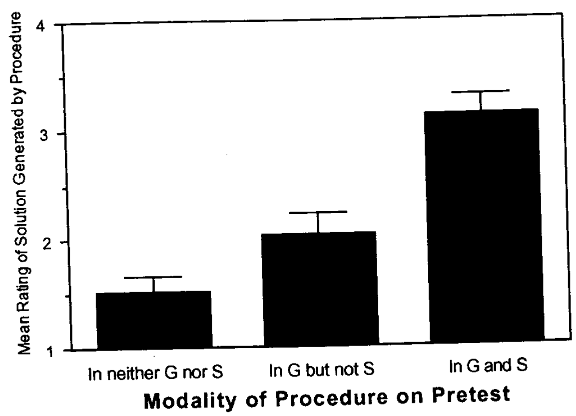

Fig. 9. Ratings of solutions generated by procedures as a function of the modality in which those procedures were produced on a mathematical equivalence pretest. The children rated solutions generated by procedures that they themselves produced, or failed to produce, on the pretest. The procedures are categorized according to the modality in which they appeared on the pretest. Procedures produced in both gesture (G), and speech (S), procedures produced in G but not S, and procedures produced in neither G nor S. The children gave significantly higher ratings to solutions generated by procedures that they produced in gesture only than they gave to solutions generated by procedures that they produced in neither modality, suggesting that they had access to, and could make use of, the information conveyed in their gestures. The bars reflect standard errors.

suggests that the information a child conveys uniquely in gesture, although never spoken, can nevertheless be accessed and judged. Thus, the gestures that a child produces do appear to reflect knowledge that the child possesses. Even if that knowledge is never articulated in speech, it can be recognized.

Note that, in the judgment task used by Garber et al., children were not actually asked to rate the procedure but rather were asked to rate the solution generated by that procedure. It is unclear whether, if given the procedure outright, children who produced the procedure in gesture but not in speech would judge that procedure acceptable. In other words, if asked directly whether a given procedure is acceptable, children might be unable to accept the procedure despite the fact that they can produce it in gesture and can accept a solution generated by it. Such a finding would suggest that the knowledge children have that they express uniquely in gesture is knowledge that is still relatively embedded in the task; at this point in development, the knowledge can be isolated and used in only a limited range of other contexts (cf. Karmiloff-Smith, 1992; see also Goldin-Meadow & Alibali, 1994).

B. Gesture and Speech Capture Different Aspects of Meaning

We have shown that, at certain times in the acquisition of a task, children possess knowledge about the task that they can express in gesture but do not, and perhaps cannot, express in speech. The obvious question is, why? Huttenlocher (1973, 1976) argued that it is not useful, and sometimes not even possible, to represent all aspects of human knowledge in spoken language. For example, a map of the East Coast of the United States is far more effective at capturing and conveying the contour of the coastline than words, even a large number of them, could ever be. Thus, Huttenlocher argued that there must be representational systems that do not involve words that humans use to encode information. Similarly, Anderson (1983) and Johnson-Laird (1983) each proposed a variety of representational systems, including systems that involve imagery, as options for encoding knowledge.

McNeill (1992) has suggested that gesture can serve as a vehicle for one of these options. Because of its mimetic properties, gesture is particularly adept at capturing global images. Indeed, one gesture tracing the outline of the East Coast of the United States is likely to be a more informative representation of the contour of the coastline than any set of sentences could be. Unlike speech, which reflects the linear-segmented and hierarchical linguistic structure dictated by the grammar that underlies it, gesture is idiosyncratic and is constructed at the moment of speaking—it is consequently free to reflect the global-synthetic image for which it is a natural representation (see Goldin-Meadow, McNeill, & Singleton, 1995, for further discussion of this point).

We suggest that, at certain moments in the acquisition of a task, gesture may be better able than speech to capture the knowledge that a child has about the task. This may be particularly true if the child's knowledge is in the form of an image that cannot easily be broken down into the segmented components that speech requires. For example, children who use their pointing fingers to pair each checker in one row of a conservation task with a checker in the second row but do not express this one-to-one correspondence in their speech may have an image in which the two rows are aligned checker-by-checker. This image is easily captured in gesture but, unless the children have an understanding of the components that comprise the image, the image is not going to be easy to express in speech.

Simon (1992; see also Tabachneck, 1992) provided an example in adults which is reminiscent of the state we describe in children. The adults are able to grasp an image and read certain types of knowledge off of it, but are not able to understand fully the relationships displayed in the image.

The adults in Simon's study were provided with a graphic display of supply and demand curves (curves showing the quantities of a commodity that would be supplied, or demanded, at various prices) and asked what the equilibrium price and quantity would be. Although often able to answer the question about equilibrium price and quantity correctly, the adults were not able to give cogent reasons for their correct responses. Simon argued that the adults were able to respond to the perceptual cues in the image presented in the graph but did not have a semantic interpretation of the meaning of these cues. We suggest that it is exactly at this point in their understanding of the problem that the adults may be able to express cogent reasons in gesture, despite their failure to do so in speech.

We end with a caveat. Although gesture may be better able than speech to capture the knowledge a child has about certain tasks, it may be less well suited for other tasks. The tasks we have explored in our studies—conservation and mathematical equivalence—are spatial in nature, leaving open the possibility that our results are specific to tasks of this sort and that speech (rather than gesture) will have privileged access to aspects of a child's knowledge in other domains. For example, because moral reasoning is more culturally and socially bound than mathematical reasoning, talk may be essential to making progress in the task. In this case, we might not expect gesture to have privileged access to insights in this domain, and information might well be expressed uniquely in speech rather than gesture at moments of transition in the acquisition of this concept. In fact, Goodman et al. (1991) reported that gesture and speech do not always match in children's and adults' responses to Kohlberg's moral reasoning tasks; however, it remains an open question as to whether insights into the task are first expressed in gesture or in speech within this domain.

C. Gesture as a Window into the Mind of the Learner

McNeill (1992) argued that gesture, like speech, can serve as a channel of observation into mental processes and representations, that is, as a window into the mind. Because spontaneous gesture is less codified than speech and is dictated by different constraints, it tends to reflect different aspects of a speaker's knowledge than does speech.

We agree with McNeill and suggest that gesture can be a particularly revealing window in children (or learners of any age) who are in transition. We suggest that the relationship between gesture and speech not only serves as an index of the transitional state, but also provides insight into the internal processes that characterize the mind of a child in transition. By observing the gestures that children produce along with speech, we have been led to a view of the transitional state as one in which more than one viewpoint is considered on a single problem. The concurrent activation of two views is seen directly in the gesture–speech mismatches children produce when explaining their solutions to a problem, one view expressed in speech and a second view expressed within the same response in gesture. It is also seen indirectly in the fact that activation of two views on a single problem takes cognitive effort and diminishes performance on a secondary task when children are actually solving the problems.

Gesture–speech mismatch itself appears to be an outgrowth of the fact that, at a certain point in the learning process, children have a set of ideas about a problem that they express in gesture but not in speech. The set of ideas that children express in gesture at this point in development is both different from, and larger than, the set of ideas the children express in speech.

Note that our characterization of the transitional state puts constraints on the types of mechanisms that can be proposed to account for learning. Any mechanism of change purported to account for this type of transition must involve two different processes. One process serves to introduce new ideas into the learner's repertoire. In the tasks we have studied, new ideas are introduced into the learner's gestural repertoire and therefore enter in a form that is readily expressed in gesture but not in speech. This first process thus results in an overall increase in the number of ideas the learner has available. A second process serves to sort out the multiple ideas in the learner's repertoire, abandoning some ideas and recoding others (perhaps by recoding the images reflected in gesture into the linear and segmented code that characterizes speech). This process thus results in a decrease in the number of ideas the learner has available, all of which are now accessible to both gesture and speech.

It is important to stress, however, that throughout the acquisition process, learners appear to have a variety of approaches to a problem (as opposed to a single, consistent approach) at their disposal. What we see during transitional periods is a marked increase in this variability—an increase that, at a minimum, serves as an index of the transitional state, and that may even be central to the learning process itself.

Acknowledgments

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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, April). *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. (1994). *Processes of cognitive change revealed in gesture and speech.* Unpublished doctoral dissertation, University of Chicago.

Alibali, M. W., Flevares, L., & Goldin-Meadow, S. (1994). Going beyond what children say to assess their knowledge. Unpublished manuscript.

Alibali, M. W., & Goldin-Meadow, S. (1993). Gesture-speech mismatch and mechanisms of learning: What the hands reveal about a child's state of mind. *Cognitive Psychology, 25,* 468–523.

Anderson, J. R. (1983). *The architecture of cognition.* Cambridge, MA: Harvard University Press.

Anderson, N. H., & Cuneo, D. O. (1978). The height + width rule in children's judgments of quantity. *Journal of Experimental Psychology: General, 107,* 335–378.

Ashcraft, M. H. (1987). Children's knowledge of simple arithmetic: A developmental model and simulation. In J. Bisanz, C. J. Brainerd, & R. Kail (Eds.), *Formal methods in developmental psychology* (pp. 302–338). New York: Springer-Verlag.

Church, R. B. (1990, May). 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.

Crowder, E. M., & Newman, D. (1993). Telling what they know: The role of gesture and language in children's science explanations. *Pragmatics and Cognition, 1,* 341–376.

Crowley, K., & Siegler, R. S. (1993). Flexible strategy use in young children's tic-tac-toe. *Cognitive Science, 17,* 531–561.

Ericsson, K. A., & Simon, H. A. (1980). Verbal reports as data. *Psychological Review, 87* (3), 215–251.

Garber, P., Alibali, M. W., & Goldin-Meadow, S. (1994). Knowledge conveyed in gesture is not tied to the hands. Manuscript submitted for publication.

Gigerenzer, G., & Richter, H. R. (1990). Context effects and their interaction with development: Area judgments. *Cognitive Development, 5,* 235–264.

Goldin-Meadow, S., & Alibali, M. W. (1994). Do you have to be right to redescribe? *Behavioral and Brain Sciences, 17,* 718–719.

Goldin-Meadow, S., Alibali, M. W., & Church, R. B. (1993). Transitions in concept acquisition: Using the hand to read the mind. *Psychological Review, 100*(2), 279–297.

Goldin-Meadow, S., McNeill, D., & Singleton, J. (1995). *Silence is liberating: Removing the handcuffs on grammatical expression in the manual modality. Psychological Review,* in press.

Goldin-Meadow, S., Nusbaum, H., Garber, P., & Church, R. B. (1993). Transitions in learning: Evidence for simultaneously activated hypotheses. *Journal of Experimental Psychology: Human Perception and Performance, 19,* 92–107.

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

Goodman, N., Church, R. B., & Schonert, K. (1991, May). *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.

Graham, T. (1994, June). *The role of gesture in learning to count.* Paper presented at the annual meeting of the Jean Piaget Society, Chicago, IL.
Graham, T., & Perry, M. (1993). Indexing transitional knowledge. *Developmental Psychology, 29,* 779–788.
Huttenlocher, J. (1973). Language and thought. In G. A. Miller (Ed.), *Communication, language, and meaning: Psychological perspectives* (pp. 172–184). New York, NY: Basic Books.
Huttenlocher, J. (1976). Language and intelligence. In L. B. Resnick (Ed.), *The nature of intelligence* (pp. 261–281). Hillsdale, NJ: Erlbaum Associates.
Iverson, J., & Goldin-Meadow, S. (1995). What's communication got to do with it? Gesture in blind children. Manuscript submitted for publication.
Johnson-Laird, P. N. (1983). *Mental models.* Cambridge, MA: Harvard University Press.
Karmiloff-Smith, A. (1992). *Beyond modularity: A developmental perspective on cognitive science.* Cambridge, MA: MIT Press.
Klahr, D. (1984). Transition processes in quantitative development. In R. J. Sternberg (Ed.), *Mechanisms of cognitive development* (pp. 101–140). New York: W. H. Freeman & Co.
Klahr, D., & Wallace, J. G. (1976). *Cognitive development: An information-processing view.* Hillsdale, NJ: Erlbaum.
Langer, J. (1969). Disequilibrium as a source of development. In P. Mussen, J. Langer, & M. Covington (Eds), *Trends and issues in developmental psychology* (pp. 22–37). New York: Holt, Rinehart & Winston.
McNeill, D. (1992). Hand and mind. Chicago: University of Chicago Press.
Momeni, C. (1994). Detection of gesture in experimental and natural conditions. Unpublished masters thesis, University of Chicago, Chicago, IL.
Nisbett, R. E., & Wilson, T. D. (1977). Telling more than we can know: Verbal reports on mental processes. *Psychological Review, 84* (3), 231–259.
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.
Perry, M., & Elder, A. D. (1994). *Knowledge in transition: Adults' developing understanding of a principle of physical causality.* Manuscript submitted for publication.
Piaget, J. (1964/1967). *Six psychological studies.* New York: Random House.
Piaget, J. (1975/1985). *The equilibration of cognitive structures.* Chicago: The University of Chicago Press.
Siegler, R. S. (1976). Three aspects of cognitive development. *Cognitive Psychology, 8,* 481–520.
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. (1984). Mechanisms of cognitive growth: Variation and selection. In R. J. Sternberg (Ed.), *Mechanisms of cognitive development* (pp. 141–162). New York: W. H. Freeman & Co.
Siegler, R. S. (1994a). Cognitive variability: A key to understanding cognitive development. *Current Directions in Psychological Science, 3,* 1–5.
Siegler, R. S. (1994b). Children's thinking: How does change occur. In W. Schneider & F. Weinert (Eds.), *Memory performance and competencies: Issues in growth and development.* Hillsdale, NJ: Erlbaum. in press.
Siegler, R. S. (1995). How does change occur: A microgenetic study of number conservation. *Cognitive Psychology, 28.*
Siegler, R. S., & Jenkins, E. (1989). *How children discover new strategies.* Hillsdale, NJ: Erlbaum.

Siegler, R. S., & McGilly, K. (1989). Strategy choices in children's time-telling. In I. Levin & D. Zakay (Eds.), *Time and human cognition: A life span perspective* (pp. 185–218). Elsevier Science: Amsterdam.
Siegler, R. S., & Shrager, J. (1984). Strategy choices in addition and subtraction: How do children know what to do? In C. Sophian (Ed.), *The origins of cognitive skills* (pp. 229–293). Hillsdale, NJ: Erlbaum.
Simon, H. A. (1992, August). *Why the mind needs an eye: The uses of mental imagery.* Distinguished Centennial Address presented at the 100th Annual Convention of the American Psychological Association, Washington, D.C. Also in *Complex Information Working Papers* (No. 499). Pittsburgh, PA: Carnegie Mellon University.
Snyder, S. S., & Feldman, D. H. (1977). Internal and external influences on cognitive developmental change. *Child Development, 48,* 937–943.
Stone, A., Webb, R., & Mahootian, S. (1992). The generality of gesture–speech mismatch as an index of transitional knowledge: Evidence from a control-of-variables task. *Cognitive Development, 6,* 301–313.
Strauss, S. (1972). Inducing cognitive development and learning: A review of short-term training experiments. I. The organismic developmental approach. *Cognition, 1*(4), 329–357.
Strauss, S., & Rimalt, I. (1974). Effects of organizational disequilibrium training on structural elaboration. *Developmental Psychology, 10,* 526–533.
Tabachneck, H. J. M. (1992). *Computational differences in mental representations: Effects of mode of data presentation on reasoning and understanding.* Unpublished doctoral dissertation, Carnegie Mellon University, Pittsburgh, PA.
Thelen, E. (1989). Self-organization in developmental processes: Can systems approaches work? In M. Gunnar & E. Thelen (Eds.), *Systems and development: The Minnesota Symposium on Child Psychology* (pp. 77–117). Hillsdale, NJ: Erlbaum.
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. 92–133). New York: Holt, Rinehart & Winston.
Turiel, E. (1974). Conflict and transition in adolescent moral development. *Child Development, 45,* 14–29.
Wilkening, F. (1980). Development of dimensional integration in children's perceptual judgment: Experiments with area, volume, and velocity. In F. Wilkening, J. Becker, & T. Trabasso (Eds.), *Information integration by children* (pp. 47–69). Hillsdale, NJ: Erlbaum.
Wilkening, F. (1981). Integrating velocity, time, and distance information: A developmental study. *Cognitive Psychology, 13,* 231–247.
Wilkening, F., & Anderson, N. H. (1982). Comparison of two rule-assessment methodologies for studying cognitive development and knowledge structure. *Psychological Bulletin, 92,* 215–237.
Wilkinson, A. C. (1982). Partial knowledge and self-correction: Developmental studies of a quantitative concept. *Developmental Psychology, 18,* 876–893.