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Knowledge in Transition: Adults' Developing Understanding of a Principle of Physical Causality

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What are the conditions that make it likely that cognitive change will occur? We investigate this issue with respect to 25 college students' developing understanding of gear movement (a particular problem in the domain of physical causation). The participants solved problems, then received minimal instruction, and solved additional problems. Significantly, only some of the participants changed their approach to solving the problems after receiving instruction; the remainder of the participants were stable in their understanding and either continued to solve all problems correctly or continued to solve key problems incorrectly. Most analyses focused on the participants who began by solving problems incorrectly. In particular, we attempted to differentiate those participants who exhibited cognitive change from those who did not. To do this, we examined precursors of knowledge change that were motivated by different theoretical positions on mechanisms of cognitive change and development (i.e., consideration of multiple approaches, cognitive conflict, and instruction as an example of a sociocultural process). Results suggest that having multiple approaches available and using instructional information to build on not-well-developed conceptions are likely candidates for understanding knowledge change for adult participants with respect to their developing understanding of physical causality.

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Understanding how old knowledge is transformed into new knowledge, or how a new approach to a problem is acquired, is an issue that psychologists and educators have faced for at least the past century (e.g., Thorndike & Woodworth, 1901) and that philosophers have pondered for even longer. Although the issue of how knowledge change occurs is perhaps the most fundamental issue in the study of cognitive development, no single theoretical perspective adequately describes and explains how knowledge change occurs, and progress in understanding this issue has been slow in coming (e.g., Siegler, 1995; Sternberg, 1984). Furthermore, many significant contributions to the understanding of cognitive change have been concentrated in studies of children's development. Although this is not necessarily problematic, it does raise the question of whether processes of cognitive change that have been uncovered for young participants are the same for older participants.

Recent research and theory implicate three mechanisms in this process, at least with respect to children's cognitive development. First, the presence of multiple approaches may provide the impetus for knowledge change to be accomplished. In other words, possessing more than one approach to the solution of any one problem may provoke the need for cognitive reorganization. Second, cognitive conflict and its resolution may be a mechanism leading to the development of new knowledge. Third, sociocultural processes may provide critical structure for the formation of new knowledge. We ask whether the mechanisms that have been hypothesized to account for knowledge change in young children also account for knowledge change in adults.

We go beyond extant investigations that have made contributions in this area (e.g., Graham & Perry, 1993; Perry, Church, & Goldin-Meadow, 1988; Siegler & Jenkins, 1989) by asking whether the same processes identified to operate for children in the logico-mathematical domain may generalize to the domain of physics and to an adult population. The extension to the domain of physics is crucial because physics represents a domain in which, unlike other academic domains (e.g., literacy), children and adults often form powerful but often incorrect conceptions; thus, understanding how physics knowledge is transformed may provide insight into the resilience or malleability of scientific misconceptions (e.g., Carey & Smith, 1993; Chinn & Brewer, 1993; Vosniadou, 1992).

The investigation of transition mechanisms in an adult population is another critical feature of this investigation. Much of the work on the sorts of transition mechanisms that we have chosen to investigate has been conducted on children under the age of 10 (but cf. Dunbar, 1993; Gentner, 1989; Ross, 1989, and others for investigations into other types of mechanisms for learning and cognitive change in adult populations). The question remains open whether adult development can be characterized by the same developmental processes identified for children and, if so, whether adult knowledge change is more dependent on some mechanisms than on others.

MECHANISMS OF KNOWLEDGE CHANGE

Multiple Approaches

One strand of theory and research that had an impact on the investigation presented here originated in Piaget's epistemology and account of cognitive development. Piaget made many contributions (e.g., 1960/1975, 1947/1985) to understanding knowledge change (one contribution, the role of conflict, is discussed further in the next section). In general, Piaget (e.g., 1947/1985) maintained that development occurred when an individual held two concepts that needed to be coordinated; this coordination naturally led to a new understanding. Thus, Piaget made it clear that the presence of multiple approaches to a particular problem (in other words, multiple concepts needing coordination) was a prerequisite to cognitive change.

More recently, others (e.g., de Ribaupierre, 1989; Karmiloff-Smith, 1984; Siegler, 1989; Siegler & Jenkins, 1989) have made similar theoretical claims and have provided substantial empirical support to explicate and support the theory. Siegler's work provides a particularly clear example of the position that relies heavily on the existence of multiple strategies as an impetus for cognitive change. Siegler and his colleagues (e.g., Siegler & Crowley, 1991; Siegler & Jenkins, 1989) investigated the appearance of multiple and variable strategy use prior to the acquisition and use of a relatively sophisticated strategy (also see Wilkinson, 1982). They advocated (Siegler & Crowley, 1991) and followed (Siegler & Jenkins, 1989) a microgenetic approach to study preschool children's developing knowledge of simple addition. Of relevance here is that Siegler and his colleagues found that just before children reach a new understanding, when their knowledge is in a state of transition, they exhibit multiple approaches to a common set of problems (e.g., sometimes recalling the solution to 2 + 3 and sometimes counting up to two and then counting three more). Moreover, during this time of transition, children use multiple strategies inconsistently. The variability and inconsistency in children's approaches results in conceptual growth because, when learners accumulate multiple approaches to a problem, they are in a position to "select" the approach that is most adaptive (Siegler, 1989). Thus, both theory and data support the argument that the presence of multiple approaches may be necessary for cognitive change to occur. Although Siegler and Piaget both examined this issue across several domains, fine-grained studies of the presence of multiple approaches as a prerequisite to adult cognitive change are rare (e.g., Champagne, Gunstone, & Klopfer, 1985).

Cognitive Conflict

The position that holding multiple approaches is a prerequisite for cognitive change may or may not specify that the multiple approaches are in conflict. Piaget's position was one that stressed that it was not enough to hold multiple approaches for change to be accomplished: The approaches had to conflict, and the conflict had to be resolved (e.g., Piaget, 1947/1985). In essence, this position suggests that a learner must grapple with multiple notions before becoming "dissatisfied" or before a reconciliation (or equilibration) occurs at a higher level of understanding (e.g., Keil, 1984; Piaget, 1947/1985). Piaget claimed further that although the conflict may have originated from external sources, the conflict must be internalized if indeed a cognitive change is to occur.

Goldin-Meadow and her colleagues (e.g., Goldin-Meadow, Alibali, & Church, 1993) contributed a body of work that closely follows both from Siegler's research documenting the availability of multiple strategies as a necessary precursor of cognitive change and from Piaget's research suggesting that cognitive conflict acts as a mechanism of cognitive change. Goldin-Meadow and her colleagues argued that multiple approaches, if they represent cognitive conflict, must be presented or activated simultaneously in the solution of any one problem. Goldin-Meadow et al. (1993) suggested that, although having multiple approaches available for the solution of any one sort of problem is important, this is not sufficient to determine whether learners indeed are in transition with respect to their understanding of that problem. They proposed that the simultaneous consideration of multiple hypotheses may prompt the resolution of these incompatible hypotheses or strategies. In other words, when multiple hypotheses are considered at once, the person experiences some sort of internal conflict that needs to be resolved, and when it is resolved, this person will have achieved a new understanding of the problem.

The important aspect for the argument presented here about the claims made by Goldin-Meadow and her colleagues is that they offer a way to operationalize cognitive conflict. They claim that when a person expresses information in speech (e.g., while explaining problem solutions) that is different from the information expressed in hand gestures, this person is experiencing cognitive conflict. Their cleverly designed studies (see, e.g., Goldin-Meadow, Nusbaum, Garber, & Church, 1993) strongly suggest that gesture–speech mismatches are produced by children who are experiencing some sort of cognitive conflict and who are likely to undergo cognitive change under conditions where favorable instructional opportunities are available (e.g., Perry, Church, & Goldin-Meadow, 1992). In a nutshell, they argued that during those phases when knowledge is in transition, it is characterized by dual (or perhaps multiple) representations, both of which are activated when attempting to explain or solve a problem; the simultaneous activation of multiple representations causes participants to express different information in different expressive modes (i.e., in speech and in gesture). Note, however, that gesture–speech mismatch as a marker of potential knowledge change has been documented largely in children. It is unknown whether adults demonstrate their cognitive conflict in this manner as well. The only attempt thus far to document gesture–speech mismatch in non-child populations (adolescents, in particular) was successful in documenting mismatches (Stone, Webb, & Mahootian, 1991). However, Stone et al. did not find any relation between mismatches and cognitive change, thus calling into question the usefulness of gesture–speech mismatch as a general indicator of knowledge in transition (but cf. Perry, Church, & Goldin-Meadow, 1992, for some of the concerns in interpreting Stone et al.'s results).

Sociocultural Effects

Although the research and theory described thus far provide compelling descriptions of what happens to learners in their acquisition of new knowledge, these accounts ignore the effects that the social environment might play in processes of knowledge acquisition. Recently, many researchers (see, e.g., Winegar & Valsiner, 1992; Wozniak & Fischer, 1993) have argued that knowledge acquisition processes are embedded in a social context and thus cannot be investigated without considering social–contextual effects. Thus, the final theoretical approach that we acknowledge here is the sociocultural approach (e.g., Rogoff, 1990; Vygotsky, 1978; Wertsch, 1985). Unlike more biologically derived approaches, the sociocultural approach pays great attention to the role of social interaction, and more particularly didactic or instructional interactions, in cognitive change. In this approach, it is often the case that instruction plays an explicit role in the construction of new knowledge.

Vygotsky (1978) eloquently (albeit sketchily) outlined how this process operates. Vygotsky pointed out that new knowledge is co-constructed within productive learning–teaching interactions. In the example of a problem-solving situation, we might look at teachers and learners working together to find a solution to a particular problem. In this example, knowledge exists first on an interpsychological plane (i.e., is shared by both the teacher and learner, but does not exist independently in the learner) and later this knowledge is transferred (through a process of internalization) to the intrapsychological plane (i.e., eventually, the learner can solve the problem without assistance). In sum, in instructional interactions, the problem is initially understood differently by the teacher than by the learner and, as the learner participates more fully, eventually is understood similarly by the teacher and the learner.

Vygotsky (1978) also wrote that learning is defined as the awakening or nurturing of incomplete functions, or functions that exist in an immature form in the learner. In this way, teachers work to highlight the knowledge that is useful for solving the problem and also provide learners with additional information that may help to solve the problem.

We find this outline very appealing but, as others have noted (e.g., Forman & Kraker, 1985; Wertsch, 1985), difficult to specify. We can interpret and then extrapolate from Vygotsky's writings (1978; Wertsch, 1985) in several ways, in an attempt to clarify and ultimately to operationalize these constructs. First, children who have knowledge that is moving from the purely social plane toward an internalized state can be interpreted as in transition with respect to that particular knowledge. Second, incomplete functions, or functions that exist in an immature form in the learner, can be understood as tacit knowledge. Recall also that incomplete functions are those functions that lie within a learner's zone of proximal development. From this, we extrapolate that those who possess tacit knowledge (or more knowledge that lies within the zone of proximal development) should benefit from instruction earlier than those without such tacit knowledge. However, this assumption awaits verification. Thus, one of the aims of the investigation presented here is to explore the role of tacit knowledge in the process of knowledge acquisition and to document whether the processes involved in making tacit knowledge explicit, originally written to describe children's development, also characterize adult cognitive development.

EXTENDING THE RESEARCH: GEARS AS A DOMAIN OF INTEREST

The concept we chose was based on a principle of gear movement. Problems based on principles of gear movement seemed optimal for investigating the role of multiple strategies, cognitive conflict, and sociocultural effects on knowledge change. With respect to implicating multiple strategies as a critical component to knowledge change, Metz (1985, 1991) found that children used multiple approaches when solving a set of similarly structured problems and provided changing explanations when confronted with gear configurations.

Another reason we focused on gear problems was that, as Schwartz and Black (1990) pointed out, it seems that everyone gestures when they solve gear problems. What this affords us, as Goldin-Meadow et al. (1993) pointed out, is that it is likely that we could come up with an operational measure of internal conflict by relying on gesture–speech mismatches because we could easily create a situation in which participants were likely to provide information both in speech and in gesture.

The final reason that we chose a principle of gear movement as the particular content of this investigation was that we had reason to suspect that at least some participants would be receptive to instructional intervention (Perry, Woolley, Graham, Freedman, & Danos, 1992). This was an important consideration because we wanted to examine the role of didactic interactions in cognitive change. The providing of instruction was additionally important because we had reason to suspect that, without some minimal favorable instructional opportunities, it would be possible that we would not witness examples of knowledge change (e.g., Hiebert & Lefevre, 1986; Perry, Church & Goldin-Meadow 1992).

In sum, this project attempts to uncover the ways in which participants move from a less to a more advanced and stable understanding of principles of gear movement. To obtain insights about mechanisms of this process, this investigation focuses on a time during which conceptual change is likely. We examine the predictors and cues that accompany and may prompt participants' conceptual gains. In particular, our intention is to investigate how adults express their transitional knowledge with respect to gear movement (i.e., with respect to displaying multiple and potentially conflicting approaches) and how intervention may have an impact on these participants' acquisition of a new understanding of this concept.

METHOD

Participants

We recruited 25 undergraduates from a large midwestern university; 17 of the participants were women and 8 were men. The participants, who volunteered, chose this study to fulfill a part of a course requirement to participate in research. The median age of the participants was 20.2 years. On average, they had 2.5 years of college education, and 60% of them had taken at least one physics class during high school or college.

Procedure

Each participant took part in a single session, individually, consisting of six segments. The entire session was videotaped and lasted approximately 35 min. The session began with an introduction by the experimenter and a warm-up problem with a picture of two gears that the experimenter asked the participant to solve. The experimenter explained that the participant should mark the target gear with an arrow, indicating the direction the gear with the person (the target gear) would turn if the handle was turned in the specified direction (see Figure 1). All participants solved the warm-up problem correctly. The experimenter went on to inform the participant that if the gear was to move in the other direction, the participant should mark the target gear going as turning in that other direction, and if the gear was not going to turn, the participant should mark an "X" next to the target gear.

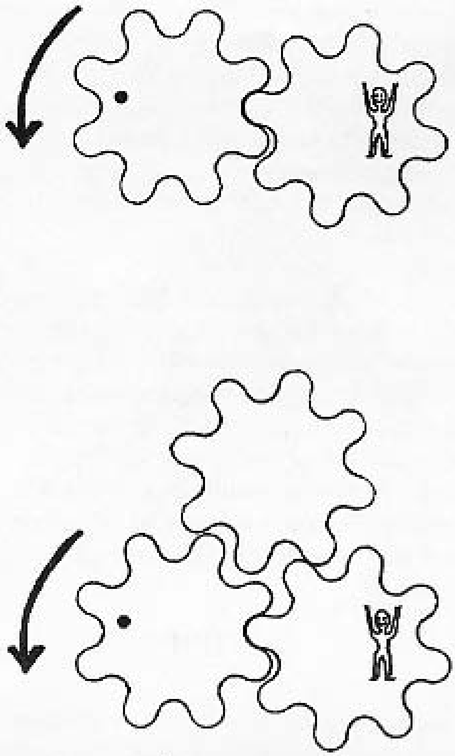

Figure 1. Top: The two-gear problem used in the warm-up task and in the first portion of the instruction. Bottom: The configuration used in the instruction.

Following the warm up, each participant completed a pretest. The pretest contained seven gear problems concerning gear movement, each presented on a separate sheet of paper. These problems appear in Figure 2. The participants were instructed to indicate whether, and if so how, a target gear, marked with a person-like figure, would move if the gear marked with a handle was moved in a specified direction. The problems varied on several dimensions, including number of gears and configuration of gears. These dimensions together determined whether the gears would move or jam. For example, both Problem 4 and Problem 6 are comprised of four gears. However, the gears in Problem 4 will turn, but the gears in Problem 6 will not turn. In simple terms, each gear attempts to turn adjacent gears in the opposite direction, so if an even number of gears form a closed loop, the gears will turn, but if an odd number of gears (e.g., 3, 5, or 7 gears) form a closed loop, those gears and all gears attached to those gears will not turn (as in Problems 5, 6, and 7).

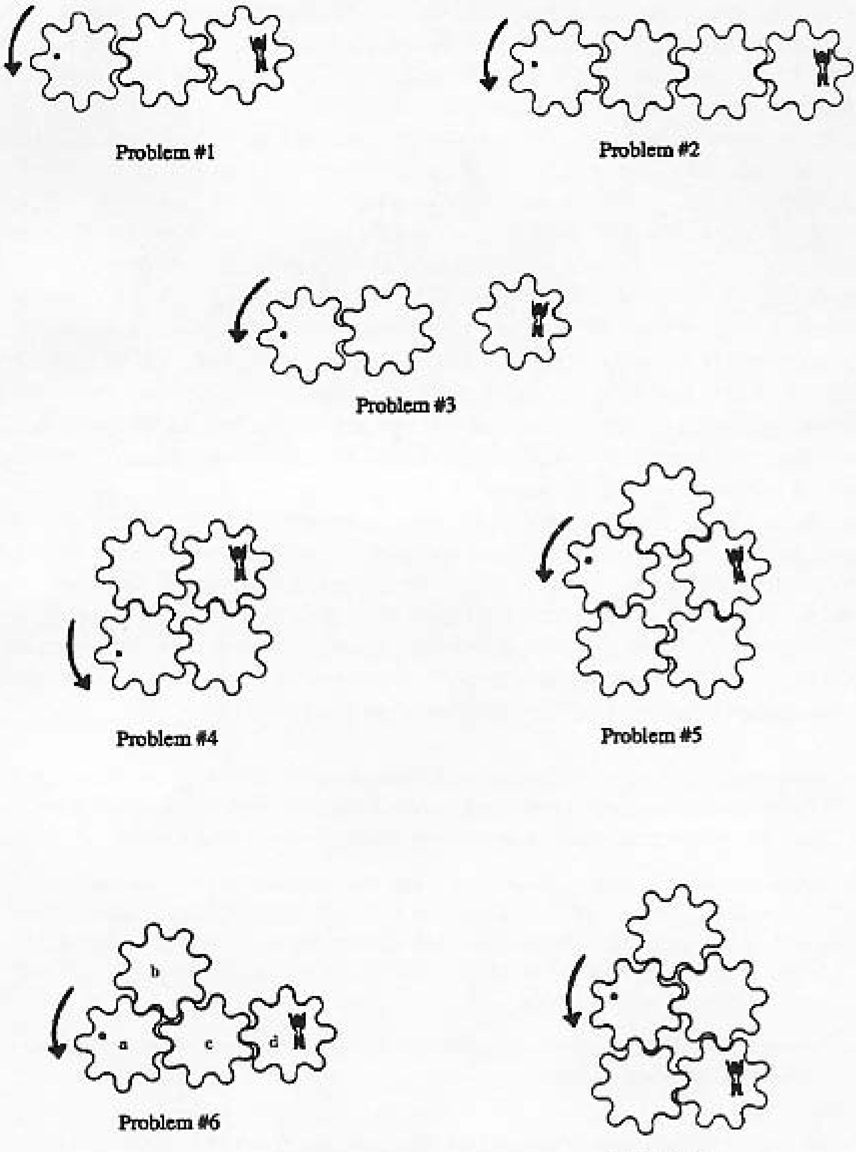

Figure 2. These are the seven problems used in the pretest. Note that the gears in Problem 6 are labeled for the reader, but were not labeled for the participants.

The pretest consisted of two parts. In the first part, the participant individually solved the gear problems (which are described in the next paragraph). In the second part, the participant provided explanations for each of the problems. The gear illustrations and the participant's solutions were available during these explanations. The primary reason for breaking the pretest into two separate phases was because the problems were novel to the participants, and we first wanted to allow participants to build some familiarity with the problems before asking for their explanations. We felt that participants would be less reluctant or hesitant and more comfortable offering their explanations after having an opportunity to become familiar with the problems than if we had asked them to offer their explanations immediately or on-line. A secondary reason was that others investigating transitional knowledge (e.g., Goldin-Meadow & Alibali, 1995) had also followed this sort of procedure. Note that participants in our study were allowed to change their solutions during their explanations. The data used for analyses were derived solely from the explanations and not from the initial problem-solving attempts.

Next, the participant explained each answer to the experimenter. This was followed by an instructional segment. The instructions were derived from elementary physics texts and were discussed with physicists before the study was run. In other words, we based the instructions on what might have been available to participants if they had consulted a textbook or an expert. Specifically, the experimenter said (beginning with a picture of a two-gear configuration, in front of the participant, as in Figure 1):

> Now I'm going to tell you something about gears. When gears move, it's because something's being pushed. So what happens with gears is that when they move, one gear's teeth are pushing against another gear's teeth.
>
> When we need a way to figure out what will happen to the gear with the person on it, one way of thinking about this is to think about the teeth. The teeth of the gear with the handle push against the teeth of each gear they touch. In the same way, the teeth of each and every gear will push against the teeth of each gear they touch.
>
> So on this problem (while pointing to the picture of two gears, see Figure 1), explain to me what's happening.

The experimenter then obtained an explanation from the participant. The experimenter went on to say:

> Now I'm going to add a third gear (see bottom of Figure 1). Now remember, the teeth of one gear push against the teeth of each gear they touch. Could you explain to me what will happen to all the gears in this problem when you try to move the gear with the handle this way?

In sum, although the instruction was minimal, it was intended to have the participants focus on two points: (a) that each gear was to be considered and (b) that the participant needed to focus on the effect of each gear's teeth on all adjacent gears. These are two critical features for understanding gear movement with respect to the problems we used in this investigation. The instructional manipulation, although brief, was intended as an experimental surrogate of a more elaborate and natural sociocultural process.

Next, the participant solved a posttest. The problems in the posttest were identical to those in the pretest, except that the initial direction of the gear with the handle on it was reversed. Finally, each participant was asked to explain his or her posttest solutions to the experimenter.

Coding Problem-Solving Approaches

All participants solved the first three pretest problems correctly. Thus, we ignored these problems for analysis. We coded for the types and combinations of problem-solving approaches that participants appeared to rely on to solve and explain each of the four remaining pretest problems. The coding system was created by the two authors. The coding categories were derived by jointly and independently viewing videotapes of the first 25% of the participants.[1] We coded for six distinct problem-solving approaches. The coding of any problem-solving approach was dependent on whether the participant took into account all of the relevant gears for solving the problem and how the participant conceived of the interactions or connections among the gears. A listing of the problem-solving approaches, with the defining criteria and examples, is presented in Table 1.

The first approach in Table 1, "recognize opposite influence on all adjacent gears," always leads to a correct answer (if the participant does not make an error in tracing a path). The remainder of the approaches are various ways participants could solve the gear problems (sometimes correctly, sometimes not) that did not account for one or both of the critical dimensions in these problems: all gears and all connections. Basing our coding system on these two critical dimensions meant that we distinguished between an approach in which a participant never indicated one or more of the gears ("recognize opposite influence on adjacent gears: ignore a gear or a subset of gears") and an approach in which a participant explicitly indicated all gears, but then qualified his or her explanation by noting that not all of the gears were relevant to determining the solution ("actively state that not all (relevant) gears are relevant to the solution of the problem"). We made this distinction because we suspect that these approaches are

[1]Reliability (percent agreement), for combined speech and gesture, for speech alone, and for gesture alone, was calculated from the data of the remaining participants.

Table 1. Criteria and Examples for Coding Problem-Solving Approaches

Approach	Gears Indicated, Connections Among Gears Described	Example
Recognize opposite influence on all adjacent gears	All gears, all connections[a]	Mmm . . . okay if this (a) goes this way, let's see, this (b) will go the opposite way, which is connected to this (c), this (c) will go this way, which again is the same direction as this one (a), so it gets stuck.
Recognize opposite influence on only some adjacent gears	All gears, not all connections	This one (a) it would move around, that one (b) would go up that way, this (c) would come around down like this and that (d) would go that way. [NB: The participant never referred to connection between gear a and gear c.]
Recognize opposite influence on adjacent gears: Ignore a gear on a subset of gears	Not all gears, not all connections	Okay, this one's (a) turning this way, which'll make this (c) go the opposite way, which'll make this (d) go the same as this one (a). [NB: The participant never referred to gear b.]
Actively state that not all (relevant) gears are relevant to the solution of the problem	All gears (but one or more dismissed), not all connections	This one (a) would cause this (c) to turn that way, and that one (d) would turn that way, and that one (b) doesn't even matter.
Not recognize opposite influence on all adjacent gears	All gears, irregular connections, views connections inconsistently	Because this one (a) would make this one (b) turn opposite, which would make this one (c) turn opposite to this one (a), so none of them could turn. [NB: The participant says that adjacent gears turning in opposite directions both *will* and *will not* move.]
Vague	Vague indication of gear(s) and/or vague reference to connections	Yeah, um this combination (then) would jam.

Note. Letters appearing in parentheses indicate the gear in the display to which the participant is referring in his or her gestures, and is marked on Figure 2, Problem 6.

[a]An exception may occur if the participant explores enough connections to realize that none of the gears in the display will move.

indicative of differences in underlying cognition regarding the ways in which gears move. In particular, when a participant explicitly stated that certain gears were unnecessary, the participant at least acknowledged the existence of the gears, and could, if deemed necessary, integrate those gears into the solution; if the gears were never acknowledged, the participant could not incorporate them into the solution.

Coding was done in several stages. First, with both the audio and video portion of the taped session available to the coders, each explanation was coded and assigned a problem-solving approach. It was possible that the participant could provide more than one explanation and also could provide more than one approach within an explanation. In both of these cases, multiple approaches were coded. Ten percent of the problems in the pretest and 8% of the problems in the posttest were coded with more than one approach. Only a very small portion of the problems (2% on the pretest and 1% on the posttest) were coded as no approach. Typically this occurred when the participant provided a solution and the experimenter failed to ask for an explanation.

Second, each participant's speech and gestures were coded independently. Based on the system developed for the combined audio and video information, each problem solution was coded as one of the six problem-solving approaches previously described. The coding of problem-solving approaches presented in speech was completed from transcriptions of participants' verbalizations on problems four through seven. While coding participants' speech, we assumed that the first gear referred to was the gear with the handle. This assumption was followed because in virtually all cases when speech was coded along with gesture, participants began their explanation by describing what happened to the gear with the handle.

Every participant produced some gestures for the explanation of each problem. The coding of the problem-solving approaches presented in gesture was completed from transcriptions of participants' gestures. Gesture transcriptions were produced by muting the sound from the video monitor and recording information on (a) the gear the participant was referring to, (b) the kinds of motions the participant made (e.g., pointing, tracing, hovering, etc.), and (c) the direction and placement of their gestures (e.g., clockwise from 3:00 to 9:00). Coding from these transcriptions was relatively straightforward because it was easy to determine to which gear the participant was referring at any point and thus to determine whether all or only some of the gears were indicated across the span of the explanation (which is one of the two criteria for coding a particular approach). In addition, it was relatively easy to determine whether all connections among gears had been included in the explanation and whether the participant was consistent in how those connections were represented (i.e., the second of the two criteria for coding a particular approach). As an example, one participant began explaining his solution to Problem 6 (see Figure 2) by pointing to the gear with the handle and tracing clockwise from about 11:00 to about 7:00. This was followed by a counterclockwise trace along the next gear (on the horizontal plane) and a clockwise trace along the target gear. This was coded as "recognize opposite influence on adjacent gears: ignore a gear or a subset of gears" (see Table 1). For the coding of both speech and gesture, multiple approaches were coded when the participant provided more than one explanation for any one problem.

To determine reliability, we independently coded the same 25% of the problems. For each problem, we included all coding opportunities in our reliability calculations. This means that if a participant produced multiple approaches, each approach was considered as a separate coding opportunity. Further, if participants did not display an approach (and no approach was coded), this was also considered an instance of a coding opportunity. Interrater agreement for the problem-solving approaches was determined by counting the number of agreements and dividing this by the total number of opportunities for coding a problem-solving approach. Interrater agreement for coding of combined speech and gestures approaches was 89%; interrater agreement for coding of verbal approaches was 88.5%; and interrater agreement for coding of gestured approaches was 94%. All disagreements were resolved by discussion. When coding the pretest, the coders were blind as to how the participants performed after instruction and, when coding the posttest, the coders were blind as to the participants' initial performance.

RESULTS

Defining Knowledge Status

We defined participants' knowledge and understanding of gears with respect to their explanations of their solutions to the four gear problems of interest (i.e., problems 4–7; see Figure 2) on the pretest compared to the posttest. Some participants showed successful understanding on both the pretest and the posttest; we refer to these participants as initially successful. Some participants showed a lack of understanding on both the pretest and the posttest; we refer to these participants as the nonlearners. The remainder of the participants initially showed a lack of understanding, but then showed successful understanding; we refer to these participants as the learners. Of the 25 participants, 9 were initially successful. Of the 16 remaining participants (64% of the sample), 6 were learners and 10 were nonlearners. We report the mean number of correctly solved problems and standard deviations in Table 2. Although the initially successful participants obviously solved more problems correctly than the other two groups of participants

Table 2. Problem-Solving Success on the Pretest and Posttest by Group

	Mean Number and Standard Deviations of Correctly Solved Problems			
	Pretest		Posttest	
Group	*M*	*SD*	*M*	*SD*
Initially successful	4.00	0	3.89	.33
Learners	2.17	.98	4.00	0
Nonlearners	1.60	.97	2.20	1.03

on the pretest (i.e., all 9 participants in this group solved all problems correctly), the learners and the nonlearners did not differ significantly on the number of problems that they solved correctly on the pretest (2.17, s.d. = .98 vs. 1.60, s.d. = .97, out of four problems). On average, the participants in both of these groups were solving about half of the four problems correctly.

For the remainder of the Results section, we examine the characteristics that differentiated the learners and the nonlearners. We took as our task to examine the information provided by the participants before they received any instruction and to compare the information expressed by the learners versus the nonlearners to gain insight into the conditions under which knowledge may or may not be transformed. At times, when informative, we also present information about the participants who were successful before instruction (initially successful) because data from these participants may be helpful in interpreting the data from the other two groups. We caution that our sample size is limited, as is the case for many studies in which participants have been further partitioned based on subsequent performance and that provide comparative detailed and in-depth analysis of multiple levels of behavior for each group of participants (e.g., Dunbar, 1993). Although our sample size is small and the power of the statistics is somewhat limited, our results remain suggestive about mechanisms of cognitive change.

Background Characteristics and Initial Knowledge

Before presenting what differentiated the participants, we report several features that did not differentiate the participants across the three groups (i.e., learners, nonlearners, and initially successful participants). The participants across the three groups did not differ substantially or significantly in terms of mean age at time of participation, gender, or number of formal physics courses taken, all $ps > .10$.

Use of Multiple Approaches

As we mentioned earlier, variability in ways children solve problems is predictive of their cognitive change. From this, we asked if the presence of multiple approaches while explaining the pretest gear problems would be related to whether our adult participants would be ready to benefit from instruction. We operationally defined this as the total number of different problem-solving approaches used in the entire set of four problems. Using ANOVA, with groups as the independent variable and number of pretest approaches as the dependent variable, we found significant differences between the groups of participants, $F(2, 22) = 6.3, p < .007$. Post hoc analyses revealed that the participants identified as learners used significantly more approaches during the pretest (mean of 3.33 approaches on the four problems of interest) than either the nonlearners (m = 2.0) or the initially successful (m = 1.8), Fisher PLSD = .938, $p < .05$ between learners and nonlearners, Fisher PLSD = .958, $p < .05$ between learners and initially successful, and that the initially successful and nonlearners were not significantly different from each other. Note that we included the initially successful participants in this analysis because, like the nonlearners, we could predict that they were not prepared to make a cognitive change in their understanding of the gear problems and thus could predict that they would rely on fewer strategies than those participants who were to make a cognitive change.

Simultaneous Use of Multiple Approaches: Evidence of Cognitive Conflict

Goldin-Meadow et al. (1993) made the point that one way to characterize knowledge in transition relies on dual (or multiple) representations that are in conflict and in need of resolution. Based on this characterization, they argued that these different representations would appear simultaneously in different modalities. Following this argument, we examined whether the multiple approaches expressed by the participants were not merely available throughout a participant's repertoire (as we have just demonstrated), but whether they were activated simultaneously in the solution of any one problem.

To examine this issue, we compared the information in speech and gesture independently and examined whether participants expressed different approaches in the two modalities when solving any one problem. Note that for the analyses just reported, we had taken into account all information produced in speech and in gesture by a participant when explaining a solution. For the analysis presented now, we realized that although information expressed in speech and in gesture could have been redundant (i.e., presenting the same information in the two expressive modalities), it also could have been unique (i.e., presenting different information in the two expressive modalities). When the approaches expressed in the two modalities were different when solving any one problem, we labeled this as a gesture–speech mismatch.

In general, the participants who learned were more likely to produce different approaches in gesture and in speech—that is, produce a mismatch between the problem-solving approach coded in the spoken explanation and the problem-solving approach coded in the gestured explanation. On average, the learners produced a mean of 2.17 (out of a possible 4) mismatches, whereas the nonlearners produced a mean of 1.40 mismatches. However, although a pattern consistent with our expectations was confirmed (i.e., that learners would demonstrate conflict—as measured by simultaneously displaying two contradictory approaches—whereas nonlearners would not), we note that the difference between learners and nonlearners did not reach conventional levels of significance, $t(14) = 1.53$, $p = .07$, one tailed.

Instructional Effects: An Example of Sociocultural Processes

We realize that, at least in part, the instruction that we provided contributed to the knowledge change that we have documented. The question that we examined next was: Can we specify how the instruction had an impact? In particular, were there aspects of the instruction that activated knowledge transformation or enabled learners to coalesce knowledge in some new way?

The instruction that we had provided focused on two things: that the participant needed to pay attention to each and every gear, and to the fact that each gear will attempt to push all adjacent gears. Because our instruction concentrated on these two features of the problem domain, we concentrated our analyses on participants' understanding of these same features, as expressed in their pretest explanations. In particular, we examined whether participants indicated each and every gear in their explanation and whether they described the effect of each gear on all adjacent gears. In this way, we could examine what knowledge the participants possessed that may have facilitated or may have discouraged the ability to make productive use of the information provided in the instruction.

All Gears. For most of the problems that we presented to participants, it was beneficial to pay attention to all of the gears in the problem. By doing so, the participants would reduce the risk of failing to notice that two adjacent gears might need to turn in the same direction, which is impossible (note that this is true for Problems 5, 6, and 7; see Figure 2).

To examine whether participants were attending to all of the gears in the problem, we assessed the total percentage of gears, in each of the four target problems, to which each participant referred (in speech and/or in gesture).

On average, the learners referred to significantly more gears on the pretest (87% of all gears) than the nonlearners (73% of all gears), $t(14) = 2.25, p < .05$, comparing the number of gears indicated.[2]

Effects of Gears on Adjacent Gears. The most sophisticated way to explain problems that were solved correctly was to comment on the effect of each gear on adjacent gears (i.e., use the "recognize opposite influence on all adjacent gears" approach). Although this approach only appeared when problems were solved correctly, it is also true that other approaches could be used to explain correctly solved problems, but these other approaches overlooked this important feature of the problems (i.e., the feature of considering effects on adjacent gears). We examined whether the learners may have been relying on the more sophisticated approach when explaining their correct solutions on the pretest and, if so, this may have served as a "bootstrap" to integrate compatible information from the instruction into their repertoire. Thus, we examined whether learners differed from nonlearners in terms of their use of the "recognize opposite influence on all adjacent gears" approach on correctly solved problems,[3] as expressed globally through both speech and gesture.

The participants who were later to benefit from instruction (the learners) justified 47% of their correct pretest solutions with an explanation that took into account the effect of each gear on all adjacent gears (i.e., used the "recognize opposite influence on all adjacent gears" approach). The participants who did not benefit from instruction justified only 5% of their correct solutions with an explanation that took into account the effect of each gear on all adjacent gears. Using an arcsine transformation on the proportion of correctly solved problems (because each participant did not necessarily have the same total number of correctly solved problems), we found that the learners were significantly more likely than the nonlearners to justify their

[2]We note that the learners were already performing at or almost at ceiling levels at the time of the pretest; thus, not much is to be gained by examining improvement to the posttest. We did, indeed, conduct this analysis and found that, as on the pretest, learners referred to a significantly greater percentage of gears than the nonlearners (95% vs. 75%), $t(14) = 2.86, p < .02$.

[3]Recall that the learners and the nonlearners were solving the same number of problems correctly on the pretest—on average, approximately two out of the four target problems. When analyzing the content of the problem-solving approaches produced by the different groups of participants, we always separated approaches used to justify or explain correct solutions from those approaches used to justify or explain incorrect solutions. We did this because we wanted to examine how the participants appeared to understand the gear movement problems for which they were able to obtain a correct solution—and not to confound these with those problems for which they did not obtain a correct solution. In other words, we did not expect to see the same approaches used to justify both correct and incorrect solutions.

correct solutions with the "recognize opposite influence on all adjacent gears" approach, $t(14) = 2.95, p = .01$.

To understand the way that instruction operated in this study, it is important to examine the participants' use of problem-solving approaches on the posttest and determine if their approaches incorporated the important aspects of the instruction. Thus, we examined participants' use of the "recognize opposite influence on all adjacent gears" approach on the posttest. We also did this to get a sense of just how fully they had generalized this approach in solving the posttest problems. In a sense, we were also examining participants' stability in successfully using the "recognize opposite influence on all adjacent gears" approach. We found that the learners relied heavily on this approach in the posttest and gave up using the other, relatively unsophisticated and/or unsuccessful approaches: The learners used the "recognize opposite influence on all adjacent gears" approach to explain 67% of all posttest solutions and used a "vague" approach to explain the remainder (33%) of their solutions. This finding is important in at least two respects. First, the proportion of the learners' use of this sophisticated problem-solving approach may be compared to their use of this approach on the pretest; in particular, they used this approach to explain only 29.2% of all of their pretest solutions. Second, this may be compared to the nonlearners' pattern of using problem-solving approaches on the posttest; overall, the nonlearners used the "recognize opposite influence on all adjacent gears" approach on only 12.5% of their posttest solutions. Thus, it appears that the learners made progress in terms of solving the posttest problems correctly and had done so in a way not matched by the nonlearners. Furthermore, it appears that the learners had picked up on the information provided in the instruction and generalized the use of the sophisticated "recognize opposite influence on all adjacent gears" approach to a majority of the problems they faced on the posttest.

We also examined whether the use of any other of the approaches for which we coded distinguished the learners from the nonlearners. We found no significant differences between groups of participants in terms of the use of any other approach. An exception to this is participants' use of one approach: "recognize opposite influence of adjacent gears: ignore a gear or a subset of gears." For correctly solved problems, learners relied on this approach significantly less than the nonlearners, $p < .05$, by Fisher Exact. However, the differential use of this approach only strengthens and affirms the previous finding that learners reliably and consistently accounted for all of the gears in a problem, whereas the nonlearners did not. These data appear in Table 3.

DISCUSSION

The major goal of this investigation was to determine the various ways in which learners might be distinguished from nonlearners, to gain an under-

Table 3. Percentage of Problem-Solving Approaches Used by Learners and by Nonlearners

	Percentage of Use on Pretest		Percentage of Use on Posttest	
Problem-Solving Approach	**Learners**	**Nonlearners**	**Learners**	**Nonlearners**
Recognize opposite influence on all adjacent gears	29.17	2.5	67	12.5
Recognize opposite influence on only some adjacent gears	20.83	2.5	0	7.5
Recognize opposite influence on adjacent gears: Ignore a gear or a subset of gears	4.17	51.25	0	37.5
Actively state that not all (relevant) gears are relevant to the solution of the problem	6.25	3.75	0	2.5
Not recognize opposite influence on all adjacent gears	4.17	11.25	0	7.5
Vague	35.42	28.75	33	32.5

standing of the features that promote knowledge change in adults with respect to problems concerning physical causality. However, these distinctions are best understood from a backdrop of features that are similar between these groups of participants. Thus, we first discuss similarities and then move to a discussion of differences between learners and nonlearners.

Similarities Between Learners and Nonlearners

Perhaps the most important point to be made about the similarities between the learners and the nonlearners was that these similarities were on easily identifiable, readily quantifiable features of the adults. For example, they had taken about the same number of formal physics courses. At first blush this may not be very surprising because we did not choose participants based on their expert or novice status. However, we did have some participants who were experts relative to other participants (i.e., those participants who had taken at least one formal physics course compared to those who had never had any formal training in physics). The results from the investigation presented here provide yet another confirmation that formal physics training may not have a large impact on everyday notions of physical causality (McCloskey, 1983).

Also recall that the learners and the nonlearners solved approximately the same number of problems correctly on the pretest. This is significant because, as Wilkinson (1982) proposed, transitional knowledge can often be detected by "partial knowledge." This implies that some participants will possess more knowledge about a concept, and the participants with more knowledge will be those who learn the concept sooner or more easily than the participants with relatively less knowledge (but cf. Brainerd, 1977). However, our learners and nonlearners did not differ in terms of initial knowledge, as measured by the most obvious measures of initial knowledge (in particular, number of problems solved correctly). Thus, we turned to more subtle indexes of differences between participants.

Differences Between Learners and Nonlearners: Multiple Approaches and Conflict

The participants differed in several ways. First, the learners had more problem-solving approaches available to them when solving the four complex target problems. This provides additional support to the conclusion of Siegler and his colleagues that multiple strategy use is related to favorable learning outcomes. This result is particularly impressive and potentially generalizable because we explored this issue in another domain and for different-aged participants than Siegler and his colleagues investigated.

This result has at least three implications, each of which may have a role in explaining how cognitive change and development occur. One implication for participants who possess multiple strategies or multiple approaches to a set of similar problems is that they may not have a consistent approach to the set of problems. The mere possession of multiple strategies or an inconsistent approach may reflect participants' state of cognitive uncertainty (Acredolo, O'Connor, & Horobin, 1989) or instability (e.g., van Geert, 1991), and might lead them to move to a more stable "attractor" state (also see Thelen & Ulrich, 1991).

Second, and moreover, participants who possess inconsistent approaches may not have a way to choose among their available approaches. In this scenario, it is easy to imagine that participants with multiple approaches available would be receptive to instruction or coaching that provided a rationale to choose among their available approaches. Our very brief instruction did just this by highlighting two features of gear movement that could be incorporated into a sophisticated and successful approach to solve all of the problems correctly. Additionally, the participants who demonstrated use of multiple approaches on the pretest and who eventually demonstrated evidence of cognitive change seemed predisposed to the information provided in the instruction, and they responded positively to that instruction. In other words, all of the participants who eventually demonstrated evidence of cognitive change had a sophisticated approach available in the pretest session and furthermore accepted the rationale to select that approach, provided in the instruction, as evidenced in their posttest explanations. This fits well with competition and selection accounts of knowledge acquisition (e.g., Cziko, 1995; Perkinson, 1984; Siegler, 1989), in which guidance or "critical feedback" concerning how to select among competing strategies is hypothesized to have an impact on which strategy ultimately is given favor.

At the very least, it appears that when participants have multiple approaches available for dealing with any one type of problem, they are ripe for cognitive change. Our data with adult participants, as well as others' data with children (e.g., Siegler, 1994), begin to argue that the availability of multiple approaches may be a critical component of a cognitive change mechanism that is developmentally invariant. Although this cannot be confirmed (given the limited ages of the participants under investigation, especially that we did not give this task to children), the evidence suggests that this is a viable possibility worth pursuing.[4]

Third and finally, the appearance of multiple approaches in a participant's repertoire may indicate that the participant is experiencing cognitive conflict with respect to the problems at hand. Although harboring multiple strategies or multiple approaches certainly does not imply harboring conflict, we have other evidence that at least permits the hypothesis that if one harbors multiple strategies, these strategies may conflict. This is partially supported by the marginally significant result that participants who eventually learned expressed two different approaches simultaneously—one approach in speech and a different approach in gesture—more often than did participants who did not learn. According to Goldin-Meadow et al. (1993), the presence of gesture–speech mismatches provides strong external evidence of the sort of internal conflict described by Piaget (1947/1985).

Although we uncovered a relation between gesture–speech mismatch and eventual progress in understanding the concept of gear movement, we caution that this finding was not very robust. We are relatively more skeptical that conflict was a driving force in producing cognitive change and development for adults than we are about the other mechanisms that we investigated. Thus, it is possible that cognitive conflict may be a mechanism of cognitive change and development that operates more for children (e.g., Ames & Murray, 1982; Bell, Grossen, & Perret-Clermont, 1985; but cf. Levin & Druyan, 1993) than for adults. One possible explanation for this is that it may be that adults are accustomed to maintaining discrepant information in mind, without any prospect of resolving the discrepancies in the near future; children, on the other hand, may be less able to maintain a state of conflict. This explanation is feasible given that adults' representational competence and abstraction abilities may allow them to hold onto potentially conflicting possibilities, whereas children may be more prone to settle on a temporary "best guess" in the face of conflicting representations of a problem situation.

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[4]We thank one of our reviewers for pointing this out to us and for suggesting that we continue our work by pursuing the same task with children. We are currently engaged in this endeavor.

As an example of this, a colleague of ours knows quite well that she is a mother and a daughter and a teacher and a researcher and a student (and many other things, too). Her 3-year-old son can happily reconcile that his mother is both a mother and a teacher, but rejects the notion that she is someone else's child while being a mother and rejects that she is both a teacher and a student. This familiar sort of anecdotal example is consistent with systematic research (e.g., Watson & Fischer, 1980) that shows that young children consider only one salient feature of an object or problem and ignore other features, whereas older children and adults can appreciate that one object or problem situation can be understood in terms of multiple features.

We provided evidence that conflict may play a role in adult cognitive change. However, because the results were marginal, we encourage further research. In particular, we would encourage research that specifically describes how internal cognitive conflict operates to produce cognitive change, especially among adults.

Differences Between Learners and Nonlearners: Differences in Explaining Pretest Solutions

We found that the participants provided subtly different information in their pretest problem-solving behavior. The participants who were to benefit from instruction incorporated significantly more gears into their explanations than participants who did not benefit from instruction. Moreover, when participants actually solved a problem correctly, the participants who were to benefit from instruction were able to provide a clear, sensible, and appropriate explanation; this was much less likely to have occurred for the participants who did not benefit from instruction. This provides evidence that the different groups of participants (the learners and the nonlearners) encoded different information about the problems.

This finding is very reminiscent of Siegler's (1976) "encoding hypothesis." In particular, Siegler found that when older and younger children were equated for initial performance, only the older children were able to benefit from identical experience. Siegler determined that this was due to younger children's less adequate encoding of relevant stimuli compared to older children's encoding. From this, Siegler concluded that the ability to encode information explained a large part of the difference in ability to acquire new information. Our results concur: When participants encode information that is relevant to solving a set of problems, those participants will be more likely to benefit from experience than participants who show no evidence of encoding that relevant information.

Although we suspect that encoding of relevant information played a role in participants' ability to learn after instruction, we do not, however, wish to gloss over how critical we suspect the match is between what the participant encodes and what particular experience is provided by the experimenter or instructor. This process bears a strong resemblance to what Vygotsky (1978) wrote about the *zone of proximal development.* Vygotsky wrote that "the zone of proximal development defines those functions that have not yet matured but are in the process of maturation" (p. 86) and that learning could be defined as the awakening or nurturing of those as-yet immature functions. Vygotsky continued: "Human learning presupposes a specific social nature and a process by which children grow into the intellectual life of those around them" (p. 88). Interpreted in this way, the participants in the investigation presented here had available "immature functions" or what we have called tacit knowledge that was not yet integrated into a coherent concept of physical causality with respect to gear movement, but, with appropriate coaching as provided by the brief instruction, were led to understand the role of each gear in the problem (or "grew into" the conceptual frame presented by the experimenter).

This general theoretical explanation also works well as a context to understand the importance of the finding that the participants who later were to benefit from instruction (i.e., learners) were more likely to justify their correct solutions with a sophisticated explanation on the pretest than the participants who did not benefit from instruction (i.e., nonlearners). What this suggests is that learners were already subtly more advanced than their peers who did not benefit from instruction. Further, when provided with a larger scheme into which to place these ideas (i.e., the instruction provided in this study), participants were likely to abandon other ideas and have evidence that this approach would work on the entire range of problems they were confronted with.

We note that the absence of a control group leaves open the possibility that the learners may have improved even without instruction (thus calling into question our claims about the interaction between initial knowledge states and instruction in the production of new understanding).[5] However, we also note that the participants in this investigation had two opportunities to demonstrate success before instruction, but only some of the participants who still failed after both of those opportunities improved after instruction (i.e., the learners, but not the nonlearners). It remains a possibility that repeated exposure to the problems would lead to improvement, but in the present investigation the only observed improvement came immediately after instruction and not after other problem-solving attempts, thus mitigating (but not obviating) the interpretation that repeated exposure and not instruction was the primary cause for improvement.

The results, when taken together, give us important clues about what knowledge, in particular, these participants had available before being pro-

[5]We thank a very careful anonymous reviewer for pointing this out to us.

vided with instruction. This particular knowledge was not in-and-of itself sufficient to allow the problems to be solved correctly. However, this knowledge eventually would allow participants to make profitable use of the instruction. Overall, this investigation yielded important insights into the knowledge acquisition process for adults. In particular, we found three indexes of transitional knowledge and implicated each of these indexes as potential mechanisms in accomplishing the transition to a relatively sophisticated and stable understanding of how gears move.

REFERENCES

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.

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

Bell, N., Grossen, M., & Perret-Clermont, A.N. (1985). Sociocognitive conflict and intellectual growth. In M. Berkowitz (Ed.), *Peer conflict and psychological growth: No. 29. New directions for child development* (pp. 41–54). San Francisco: Jossey-Bass.

Brainerd, C.J. (1977). Cognitive development and concept learning: An interpretive review. *Psychological Bulletin, 84,* 919–939.

Carey, S., & Smith, C. (1993). On understanding the nature of scientific knowledge. *Educational Psychologist, 28,* 235–251.

Champagne, A.G., Gunstone, R.F., & Klopfer, L.E. (1985). Effecting changes in cognitive structures among physics students. In L.H.T. West & A.L. Pines (Eds.), *Cognitive structure and conceptual change* (pp. 163–187). New York: Academic.

Chinn, C.A., & Brewer, W.F. (1993). The role of anomalous data in knowledge acquisition: A theoretical framework and implications for science instruction. *Review of Educational Research, 63,* 1–49.

Cziko, G. (1995). *Without miracles.* Cambridge, MA: Bradford.

de Ribaupierre, A. (1989). *Transition mechanisms in child development: The longitudinal perspective.* New York: Cambridge University Press.

Dunbar, K. (1993). Concept discovery in a scientific domain. *Cognitive Science, 17,* 397–434.

Forman, E.A., & Kraker, M.J. (1985). The social origins of logic: The contributions of Piaget and Vygotsky. In M. Berkowitz (Ed.), *Peer conflict and psychological growth: No. 29. New directions for child development* (pp. 23–39). San Francisco: Jossey-Bass.

Gentner, D. (1989). The mechanisms of analogical learning. In S. Vosniadou & A. Ortony (Eds.), *Similarity and analogical reasoning* (pp. 199–241). New York: Cambridge.

Goldin-Meadow, S., & Alibali, M.W. (1995). Mechanisms of transition: Learning with a helping hand. In D. Medin (Ed.), *The psychology of learning and motivation* (Vol. 33, pp. 115–157). New York: Academic.

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

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

Graham, T., & Perry, M. (1993). Indexing transitional knowledge. *Developmental Psychology, 29,* 779–788.

Hiebert, J., & Lefevre, P. (1986). Conceptual and procedural knowledge in mathematics: An introductory analysis. In J. Hiebert (Ed.), *Conceptual and procedural knowledge: The case of mathematics* (pp. 1–27). Hillsdale, NJ: Erlbaum.

Karmiloff-Smith, A. (1984). Children's problem solving. In M. Lamb, A.L. Brown, & B. Rogoff (Eds.), *Advances in developmental psychology* (Vol. 3, pp. 39–90). Hillsdale, NJ: Erlbaum.

Keil, F.C. (1984). Mechanisms of cognitive development and the structure of knowledge. In R.J. Sternberg (Ed.), *Mechanisms of cognitive development* (pp. 81–100). New York: Freeman.

Levin, I., & Druyan, S. (1993). When sociocognitive transaction among peers fails: The case of misconceptions in science. *Child Development, 64,* 1571–1591.

McCloskey, M. (1983). Naive theories of motion. In D. Gentner & A.L. Stevens (Eds.), *Mental models* (pp. 299–324). Hillsdale, NJ: Erlbaum.

Metz, K.E. (1985). The development of children's problem solving in a gears task: A problem space perspective. *Cognitive Science, 9,* 431–471.

Metz, K.E. (1991). Development of explanation: Incremental and fundamental change in children's physics knowledge. *Journal of Research in Science Teaching, 28,* 785–797.

Perkinson, H.J. (1984). *Learning from our mistakes: A reinterpretation of twentieth-century educational theory.* Westport, CT: Greenwood Press.

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

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

Perry, M., Woolley, J., Graham, T., Freedman, A., & Danos, A. (1992, April). *The impact of verbal and manipulative instruction on understanding the movement of gears.* Paper presented at the annual meeting of the American Educational Research Association, San Francisco.

Piaget, J. (1975). *The psychology of intelligence.* Totowa, NJ: Littlefield, Adams & Co. (Original work published 1960)

Piaget, J. (1985). *The equilibration of cognitive structures.* Chicago: University of Chicago Press. (Original work published 1947)

Rogoff, B. (1990). *Apprenticeship in thinking: Cognitive development in social context.* New York: Oxford University Press.

Ross, B.H. (1989). Remindings in learning and instruction. In S. Vosniadou & A. Ortony (Eds.), *Similarity and analogical reasoning* (pp. 438–469), New York: Cambridge.

Schwartz, D.L., & Black, J.B. (1990, April). *The induction of rules from analog, mental models.* Paper presented at the annual meeting of the American Educational Research Association, Boston, MA.

Siegler, R.S. (1976). Three aspects of cognitive development. *Cognitive Psychology, 8,* 481–520.

Siegler, R.S. (1989). Mechanisms of cognitive development. *Annual Review of Psychology, 40,* 353–379.

Siegler, R.S. (1994). Cognitive variability: A key to understanding cognitive development. *Current Directions in Psychological Science, 3,* 1–5.

Siegler, R.S. (1995). How does change occur: A microgenetic study of number conservation. *Cognitive Psychology, 28,* 225–273.

Siegler, R.S., & Crowley, K. (1991). The microgenetic method: A direct means for studying cognitive development. *American Psychologist, 46,* 606–620.

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

Sternberg, R.J. (Ed.). (1984). *Mechanisms of cognitive development.* New York: Freeman.

Stone, A., Webb, R., & Mahootian, S. (1991). The generality of gesture–speech mismatch as an index of transitional knowledge: Evidence from a control-of-variables task. *Cognitive Development, 6,* 301–313.

Thelen, E., & Ulrich, B.D. (1991). Hidden skills. *Monographs of the Society for Research in Child Development, 56* (1, Serial No. 223).
Thorndike, E.L., & Woodworth, R.S. (1901). The influence of improvement in one mental function upon the efficiency of other functions. *Psychological Review, 8,* 247–261, 384–395, 553–564.
van Geert, P. (1991). A dynamic systems model of cognitive and language growth. *Psychological Review, 98,* 3–53.
Vosniadou, S. (1992). Knowledge acquisition and conceptual change. *Applied Psychology, 41,* 347–357.
Vygotsky, L.S. (1978). *Mind in society.* Cambridge, MA: Harvard University Press.
Watson, M.W., & Fischer, K.W. (1980). Development of social roles in elicited and spontaneous behavior during the preschool years. *Developmental Psychology, 16,* 483–494.
Wertsch, J.V. (1985). *Vygotsky and the social formation of mind.* Cambridge, MA: Harvard University Press.
Wilkinson, A.C. (1982). Partial knowledge and self-correction: Developmental studies of a quantitative concept. *Developmental Psychology, 18,* 874–891.
Winegar, L.T., & Valsiner, J. (Eds.). (1992). *Children's development within social context* (Vol. 2). Hillsdale, NJ: Erlbaum.
Wozniak, R.H., & Fischer, K.W. (Eds.). (1993). *Development in context: Acting and thinking in specific environments.* Hillsdale, NJ: Erlbaum.