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Verbal Imprecision as an Index of Knowledge in Transition

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Children can be verbally imprecise when they are learning, but this phenomenon is not well documented. Verbal imprecision, anecdotally referred to as "hemming and hawing," may be indexed by restatements, comments on one's lack of knowledge, deletions of sentence constituents, and pauses. The authors examined whether they could quantify indexes of verbal imprecision and use them to predict changes in problem-solving performance. Four types of verbal imprecision were found to predict improved performance. Results were used to make inferences about processes of knowledge change. In particular, evidence suggests that adopting a new approach and rejecting an old one may be independent, and ordered, processes. Although others have drawn similar conclusions, using verbal imprecision as the data source is a relatively unique and readily accessible method for lending support to this model of knowledge change.

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How does knowledge change? This very large question has received much attention (e.g., Goldin-Meadow, Alibali, & Church, 1993; Perry & Elder, 1997; Piaget, 1975/1985; Siegler, 1996). Still, there is much to learn about how cognitive change is accomplished. Many researchers (e.g., Goldin-Meadow, Nusbaum, Garber, & Church, 1993; Perry, Church, & Goldin-Meadow, 1988, 1992; Siegler, 1995; Siegler & Jenkins, 1989) have suggested that one can understand the phenomenon of cognitive change by closely examining periods when knowledge undergoes rapid change. This is possible both because it is likely that one can discover how change occurs if one watches it as it happens (e.g., Siegler & Crowley, 1991; Thelen & Ulrich, 1991) and because the behavioral indexes of transition themselves can be exploited as clues for how development occurs (e.g., Perry & Elder, 1997).

The goal of our investigation was to examine a possible cluster of indexes of transitional knowledge, verbal imprecision, for illuminating processes of cognitive change. In particular, we examined several types of imprecision in children's verbal utterances as children solved problems representing a concept of physical causality: gear movement. More generally, verbal imprecision has been hypothesized to signal cognitive change because it has been presumed that when children are in the process of cognitive reorganization, they are expending great amounts of mental energy on accomplishing the reorganization rather than on producing precise verbal utterances (e.g., Graham & Perry, 1993). In other words, during times of transition, children's verbal utterances suffer at the expense of working hard on understanding a concept or solving a problem in a new way. Although this makes a good deal of sense, the particular ways in which imprecision serves to index an impending change in knowledge have not been carefully specified. For example, it is not known whether all children express verbal imprecision in similar ways when they are learning something new. Furthermore, if children express verbal imprecision in different ways, we would like to know whether the different ways in which children are imprecise are related to the magnitude of the cognitive reorganization. Thus, we chose to examine verbal imprecision because the ways in which imprecision are implicated in cognitive change processes have been hypothesized and anecdotally described but not well articulated.

Several researchers (e.g., Caron & Caron-Pargue, 1976; Graham & Perry, 1993; Hosenfeld, van der Maas, & vanden Boom, 1997; Siegler & Jenkins, 1989; Wagner, 1987) have already suggested or documented that children become vague and inarticulate when their knowledge is unstable and in transition. Although prior studies have described this phenomenon, much of the supporting evidence has been anecdotal. We also note that researchers who have investigated verbal imprecision during times of transition have not necessarily focused on the same behavioral manifestations of imprecision. It is possible that each of the reports of verbal imprecision is a behavioral manifestation of the same underlying cause, although this is not necessarily the case. For example, it is possible that both being inarticulate as measured by revising one's explanation and being inarticulate as measured by the production of long pauses in the course of an explanation indicate the same

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underlying phenomenon (e.g., attempting to access an existing strategy that is difficult to access). However, it is also possible that they indicate different underlying phenomena (e.g., developing a new strategy vs. attempting to access an existing strategy). In response to these issues, our study provides operational definitions and data for several measures of the phenomenon of verbal imprecision. Because only a handful of reports are available, we review the major findings of each and then summarize these findings because these studies were instrumental in the development of our measures and our thinking about how different forms of verbal imprecision might capture different aspects of transitional knowledge.

Siegler and Jenkins (1989) investigated children's acquisition of a particular addition strategy. They reported that children's explanations on both the trial in which the children discovered the new strategy and the trial immediately preceding the discovery were less articulate and less clear than explanations for other trials. In particular, they reported that "false starts, long pauses, and slow counting all accompanied many children's discoveries" (Siegler & Jenkins, 1989, p. 106) and that children "became strikingly less articulate on the trial on which they discovered the new strategy. As on the trial immediately before the discovery, pauses, incomplete sentences, and multiple starts and stops characterized these discovery trials" (p. 108). They hypothesized that the source of these behaviors stemmed from "demands on mental resources, incomplete segregation of new strategies from previous ones, lack of conceptual understanding of the new acquisition, and absence of labels for describing [the new discovery]" (p. 109). Although Siegler and Jenkins provided good observations of inarticulateness and several possible underlying causes of these behaviors, we do not know whether these sorts of behaviors tend to co-occur and, especially if not, whether different manifestations of inarticulateness represent different or a common core of transition processes.

Caron and Caron-Pargue (1976) reported similar observations. They noted changes in children's explanations of a mathematical puzzle task as their ability to solve the puzzle improved. As the children's ability progressed, the language used in descriptions of their solution became characterized by less precision, less description of action, more vague action, and more reflexive verbs.

Wagner's (1987) work was built on the premise that children who displayed the simultaneous use of different strategies across modalities (i.e., one strategy in speech and a mismatching strategy in gesture, labeled *discordant* children) were more likely to be in transition than children who displayed the use of a consistent strategy across modalities (labeled *concordant* children) when explaining solutions to Piagetian conservation problems. From this premise, Wagner investigated whether children who were discordant were also more verbally imprecise than children who were concordant. Wagner reported that discordant children produced significantly more false starts, self-repairs, deletions, inconsistent referring forms, and atypical semantic relationships than concordant children. Although others (e.g., Church & Goldin-Meadow, 1986; Perry et al., 1988) have found that discordant children were significantly more likely to be in a transitional knowledge state than concordant children, Wagner did not investigate whether her measures of verbal imprecision alone could be used to predict transitional status. Thus, although it is known that these particular measures of verbal imprecision are related to the simultaneous display of two strategies (i.e., mismatching strategies in speech and gesture), it is not known whether they are related to transitional knowledge.

Graham and Perry (1993) found that children who were vague in explaining their solutions to mathematical equivalence problems were significantly more likely than children who were explicit to accomplish a cognitive change (measured by benefiting from instruction). Graham and Perry proposed that during times of transition, children were spending mental energy to reorganize their knowledge, and this prevented them from devoting the necessary effort to produce explicit, well-formed explanations. Relative to Wagner's (1987) findings, Graham and Perry reported that children who were vague were not necessarily discordant and that the two indexes of transitional knowledge (gesture–speech mismatches and verbal vagueness) measured potentially different aspects of children's underlying cognitive states. Although the two indexes of transitional knowledge reported by Graham and Perry appeared to tap different aspects of transitional processes, these indexes were represented across modalities (i.e., included both speech and gesture) and thus cannot address the question we have about whether different forms of verbal imprecision tap different aspects of the transitional process.

Finally, Hosenfeld et al. (1997) described a "critical slowing down" when children make shifts in their analogical-reasoning problem solving. Hosenfeld et al. operationally defined critical slowing down on the basis of total solution times. They reasoned that children take longer to solve problems during times of transition because systems in transition require a longer period of recovery than do stable systems. In other words, during times of stability, behaviors are more or less automatized, but during times of transition, the critical behaviors should take longer to execute (in this case, solving analogical-reasoning problems). Siegler and Jenkins (1989) also reported that children's solution times were much longer on the trial immediately before they made a discovery. However, Siegler and Jenkins suggested a different cause for this slowing down than Hosenfeld et al.: Siegler and Jenkins attributed the long solution times to "some type of cognitive conflict or interference" (p. 101) rather than to an increase in recovery time, as suggested by Hosenfeld et al. Even when two independent publications note the same behavior accompanying a transition, there is not an agreement about why this particular behavior has appeared.

To obtain a better understanding of whether, for example, lengthy solutions indicate cognitive conflict or whether the system requires a longer period of recovery when in an unstable state, it is useful to compare multiple measures of transition and see which co-occur. If patterns of co-occurrence are discovered for some, but not other, measures of verbal imprecision expressed during times of cognitive transition, then these patterns can be used to draw inferences about underlying processes of transition.

Unfortunately, we were unsure not only about the cause of lengthy solutions but also about the specific behaviors that filled the response time. For example, we can imagine that an extended response could be the result of producing a very long pause, of starting the response over (i.e., false starts), of producing extra utterances that other respondents do not tend to produce (e.g., metacognitive comments), or some combination of these behaviors. To get at the cause of lengthy solutions that appear during times of transition, we investigated several different behaviors that could each cause lengthy solutions.

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In sum, several studies (Caron & Caron-Pargue, 1976; Graham & Perry, 1993; Hosenfeld et al., 1997; Siegler & Jenkins, 1989; Wagner, 1987) have already provided evidence that children who appeared to be in a state of transition were inarticulate. This finding was true when children were solving a variety of tasks, including mathematical puzzles, addition problems, mathematical equivalence problems, analogical-reasoning problems, and Piagetian conservation tasks. These studies strongly implied that verbal indexes of transitional knowledge exist, although none of these studies systematically investigated the specific components of speech that might predict transitional knowledge. Furthermore, these studies did not explore how the different potential indexes of inarticulateness are common (tapping the same underlying phenomenon) or unique (tapping different aspects of the phenomenon of transitional knowledge).

Gear Movement

This study was designed to examine several measures of verbal inarticulateness as predictors of transitional knowledge states relating to the particular concept of gear movement. We chose the concept of gear movement for several reasons. First, past research has suggested that at least some participants change their problem-solving approach(es) following instruction on gear movement (Metz, 1985; Perry & Elder, 1997). Following this past research, if we provided instruction, we would be likely to witness cognitive change. This is crucial because we wanted to concentrate our investigative efforts during periods of rapid change to gain a detailed look at the nature of cognitive change. More precisely, the possibility of rapid change in understanding gear movement allowed us to deliver instruction and then witness change in some of the participants and then compare behavioral indexes between the participants who did and those who did not make changes in their problem-solving approaches (see, e.g., Alibali & Goldin-Meadow, 1993, for a similar research paradigm).

Significantly, and in addition, much research has shown that children and adults have incorrect and naive conceptions of physical causality (Carmazza, McCloskey, & Green, 1981; McCloskey, 1983; Perry & Elder, 1997). Researchers who focus on these sorts of problems have the opportunity to understand ways in which to overcome these naive beliefs and find ways to help children develop a relatively sophisticated understanding of how their world works.

Because children who are in transition tend to benefit from instruction, this study also examined the effects of various instructional conditions on the development of children's understanding of gear movement. It is not known what types of instruction facilitate conceptual gains on gear problems among children. It is possible that cognitive change can occur more easily after one type of instructional intervention than after another. The instructional conditions in this experiment were graded (the first condition provided minimal opportunities to learn, the second condition provided more opportunities than the first, the third condition provided more opportunities than the second, etc.). In this way, the instructional interventions were designed to examine the types of interventions necessary to promote cognitive change.

In summary, this study attempted to identify verbal predictors of cognitive change among children solving gear movement problems by examining children's verbal explanations. The explanations of children who improved in their problem solving were compared with those who did not improve for evidence of different sorts of verbal imprecision. In addition, this study examined the effects of five instructional interventions to see if any one intervention was more likely to lead to cognitive change than the others.

Method

Participants

Participants were recruited from elementary schools in small Midwestern communities. Information letters describing the study were sent to the parents and students. In total, 115 fifth graders with a mean age of 11 years 1 month, ranging from 9 years 11 months to 12 years 6 months, participated in the study. Seventy-one female students and 44 male students originally participated. Most of the students were from lower-middle-class Caucasian families in rural communities. Fifth-grade students were chosen because previous research (e.g., Metz, 1985; Perry, Woolley, Graham, Freedman, & Danos, 1992) found that some fifth graders could solve gear problems correctly but also found that almost no younger (third-grade) children could solve these problems correctly.

Procedure

Students were tested individually in a quiet room in the school. All sessions were videotaped. The experimenter began by showing the students a picture of two gears and asked if they knew anything about how gears worked. Next, the experimenter gave the students a warm-up problem, which consisted of two gears. The students were asked to indicate which way the gear marked with a person would move if the gear marked with a handle (the dot, which was explicitly labeled as representing the handle) moved in the given direction (see Figure 1).

Pretest. After this warm-up problem, the students were given seven problems to solve, each on a separate sheet of paper (see Figure 2). The problems varied in the number of gears involved and in the configuration of the gears. In general, gears that are touching and arranged linearly (i.e., Problems 1 and 2 in Figure 2) will move, and each gear moves in the opposite direction of adjacent gears. Gears arranged in a closed figure will move if there are an even number of gears that comprise the closed form (i.e., Problem 4 in Figure 2). Each gear in Problem 4 will turn in the opposite direction of adjacent gears. For closed figures with an odd number of adjacent gears, the configuration will jam (i.e., the system is frustrated), and none of the gears will move (i.e., Problems 5, 6, and 7 in Figure 2). Also, a gear that is not touching gears that are turning will not move on its own (Problem 3 in Figure 2).

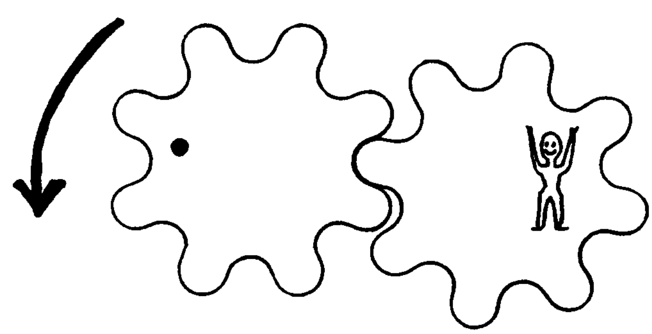

Figure 1. The warm-up problem given prior to the pretest. The child was asked to indicate which direction the gear with the person on it would move if the gear with the handle (the dot) moved in the given direction.

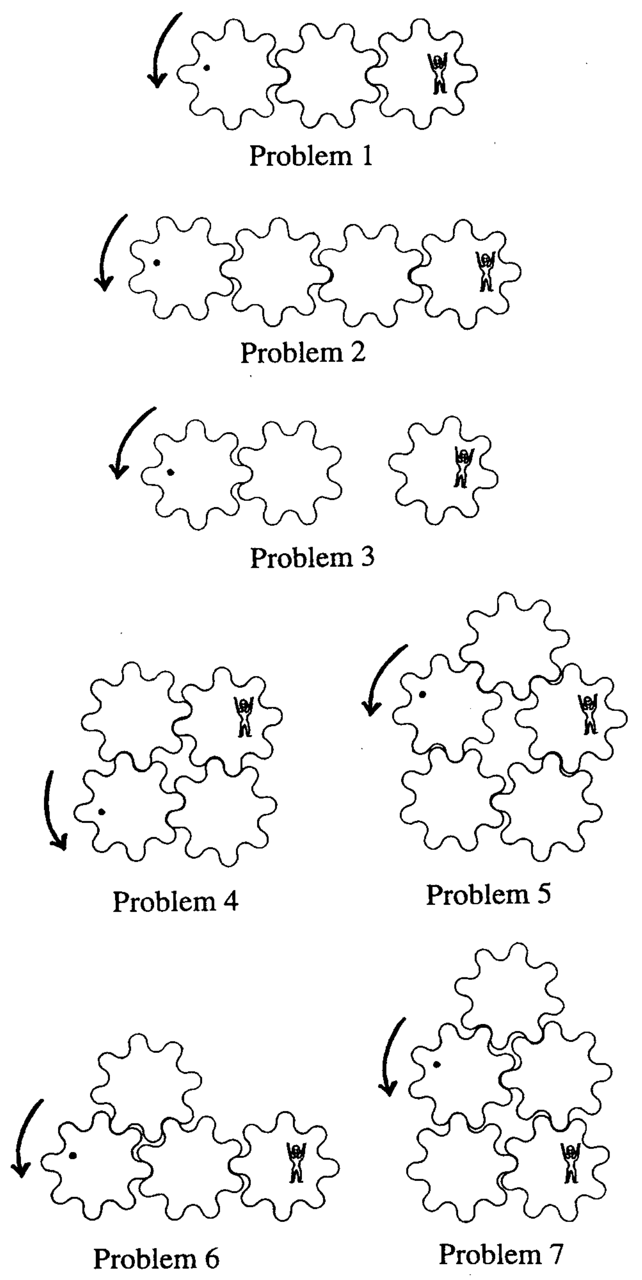

Figure 2. The seven problems given during the pretest and the posttest.

The students began the pretest by solving the seven problems on their own and marked in which direction the target gear (the gear with the stick figure on it) would move. After they solved all seven problems, the students explained their solutions to the experimenter. The pretest was broken up into two phases in this way so that the participants would get a chance to become familiar with the gears and feel comfortable with the problems before having to explain their solutions to the experimenter. This procedure of problem solving followed by explanation has been used in several other published reports that have investigated knowledge in transition (e.g., Church & Goldin-Meadow, 1986; Perry & Elder, 1997). We also note that this is very typical of how children are asked to participate in classroom contexts. Oftentimes teachers provide students with opportunities to solve a set of problems and then call on students to report how they derived their solutions. Thus, this method has high external validity.

Students who answered all seven questions correctly on the pretest (i.e., before any intervention) were omitted from further participation because they did not qualify for potentially undergoing a change from solving at least some problems incorrectly to solving all problems correctly. Thus, they were also omitted from a majority of analyses because they solved all problems correctly at the time of the pretest and could not be observed to accomplish the transition that we were interested in observing (i.e., were at ceiling levels of performance at the beginning of the study). Only 7 students solved all problems correctly at the time of the pretest and thus were included only in selected analyses.

Instructional intervention. After the students explained their solutions to the pretest, any child who answered any of the problems incorrectly was then exposed to one of five instructional interventions. Overall, 108 (68 girls, 40 boys) or 94% of the 115 students answered at least one of the problems incorrectly and went on to the next phase of the study. Each of the participants was randomly assigned to one of the instructional conditions. Unfortunately, 10 of the videotapes were defective (e.g., the audio portion was missing because the microphone was plugged in incorrectly). This left analyzable data for 98 remaining students. The five interventions are summarized in Table 1.

The instructional interventions differed primarily in the level of specificity of the instructions. In the first condition, *manipulation only,* the students were instructed to play with real gears but received no additional instruction. In the second condition, *consider all gears,* the students were told to consider all of the gears when solving the problems. This information was minimal, but critical, for figuring out how to solve the problems, as determined by evaluating responses of adults who learned how to solve similar problems (Perry & Elder, 1997). In the third condition, *verbal principle alone,* the students were told that the teeth of one gear push against the teeth of its neighboring gears. This verbal principle was derived from physics books written for children and discussed with physicists. Students who follow this principle should notice that the teeth of one gear move in one direction, making the teeth of the adjacent gear move in the opposite direction. Using this principle, the students should see that adjacent gears will move in opposite directions and thus should answer the problems correctly. In the fourth condition, *verbal principle plus picture,* the students were told the same principle described in the verbal-principle-alone condition but also were shown a picture to provide them with a referent for the verbal information (Levin, 1983; Mayer, 1989). In the final condition, *verbal principle plus picture plus manipulation,* the students were given all the information contained in the other four conditions. They were given the same principle as in Condition 3, shown the same picture as in Condition 4, told to pay attention to each gear as in Condition 2, and allowed to play with real gears as in Condition 1. Each instructional session was sandwiched between the experimenter asking the children to talk about how they thought gears worked and to try what they learned in the instruction on a new problem. The instructional interventions lasted, on average, from 5.52 min to 15.14 min. The mean instructional times are shown in Table 1.

Posttest. After the instructional intervention, the students were asked to solve the seven problems again in the same order. The only difference between the pre- and posttest problems was that the direction of the gear with the handle was reversed. As in the pretest, the students solved the seven problems individually and then explained each solution to the experimenter.

Follow-up session. Within 2–3 weeks after this initial session, the students were retested using the same procedure. As in the initial session, the students were given the pretest, instructional intervention, and then the posttest. The students were given the same instructional intervention during this follow-up session as they were during the initial session. The second session was included because very few students have the opportunity to work with gears and we felt it necessary for students to have multiple opportunities to work with the gear problems and to use the instructional information if we were to see gains in their problem-solving performance.

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Table 1
Summary of Instructional Interventions

Condition	Instructional intervention	No. of children	Description	Average time (in minutes)
1	Manipulation only	18	The children were allowed to spend a few minutes playing with real gears.	6.40
2	Consider all gears	22	The children were told to pay attention to every gear when solving the problems.	5.52
3	Verbal principle alone	18	The following information was given to the students: "When gears move, it's because something is 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 that they touch. In the same way, the teeth of each and every gear will push against the teeth of each gear they touch."	5.80
4	Verbal principle + picture	18	The same verbal principle was told to the students plus they were shown a picture of gears to help visualization of the principle.	6.05
5	Verbal principle + picture + manipulation (with real gears)	22	The same principle was given to the students, but they also were encouraged to investigate the principle for a few minutes using real gears. They also were reminded to pay attention to each gear in the problem.	15.14

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Additional debriefing was offered to every student but was provided only if the student expressed interest. All feedback about the correctness of the solutions was withheld until the debriefing session.

Coding Verbal Imprecision

The students' verbal explanations of their solutions during the pretest were coded for the occurrences of verbal imprecision. Only the verbal explanations from the initial pretest were examined for the presence of imprecision that we used to predict learning outcome because these were the only explanations that were not contaminated by instruction. We focused on four types of verbal imprecision, which are listed in Table 2. For each of these indexes, the number of occurrences was totaled across all seven problems.

False starts and self-repairs. The participants would, at times, begin a sentence but then start over or rephrase the sentence from somewhere in the middle of the statement. For example, 1 participant said, "This one goes, this one goes uh, this one goes up," and another participant said, "This one goes this way, no that way." On the basis of work reported by Wagner (1987), we labeled these sorts of verbal imprecision as *false starts* and *self-repairs.* Originally, we attempted to code false starts and self-repairs separately, but such statements tended to co-occur. In other words, we often found that children would self-repair at the beginning of their explanations. This meant that we could not reliably separate false starts and self-repairs, thus leaving us confused about whether to code a particular instance as a false start or a self-repair. For these reasons, all instances of false starts and self-repairs were treated alike and coded as representing one category of verbal imprecision.

False starts and self-repairs were taken to indicate a search for the right words to describe the recently used problem-solving strategy or perhaps to indicate a search for the problem-solving strategy itself. Frequent false starts and self-repairs were surprising in the testing context, especially because these children had already gone through and solved all of the problems. However, as Siegler (e.g., 1994, 1996) has pointed out, when undergoing cognitive change, one works with multiple strategies. This becomes important in understanding the production of false starts and self-repairs: If the participant is working with multiple strategies, it is likely that the participant will have difficulty accessing the strategy he or she just used to solve the problem.

Metacognitive comments. Although we asked our participants only to explain how they had solved the problem (in particular, how they had figured out that the gear with the person would turn in the direction indicated on their problem-solving sheet), sometimes participants would comment directly on their problem-solving processes in addition to explaining what they had done. For example, we heard participants say "I'm confused here" and "Wait a minute, I made a mistake." All statements that explicitly commented on the problem-solving process were coded as metacognitive comments. Siegler and Jenkins (1989) anecdotally described such comments as the awkward statements children tended to make when in transition. These comments tend to indicate confusion.

Deletions. We captured our participants sometimes not speaking in complete sentences. In particular, we found that sometimes they would

Table 2
Summary of Coding System

Category	Description
False starts and self-repairs	Includes both false starts and self-repairs; repeated statements or statements that include backtracks and corrections
Metacognitive comments	Statements that explicitly relate to the problem-solving process
Deletions	Statements in which a constituent, such as a noun or verb phrase, is omitted
Long pauses	Number of pauses longer than 3 s

delete nouns or verbs, which were often necessary for fully understanding the utterance. For example, 1 child said, "This gear will go this way, go this way, and go this way." As can be noted from this example, two noun phrases ("this gear" and "this gear") were omitted. Wagner (1987) also reported deletions in her data. Although we cannot be certain about the cause of deletions, they clearly indicate a failure to represent an idea in a complete form. On the basis of our repeated observations of the videotapes, this incompleteness was reminiscent of times when all of our efforts were geared toward producing some new, potentially fleeting, ephemeral idea and we blurted out critical features and omitted the nonessential aspects of our ideas.

Long pauses. Both Siegler and Jenkins (1989) and Wagner (1987) noted that children tended to hesitate when they learned a new concept. Our measure of hesitation was the long pause. We saw the long pause as comparable to what Hosenfeld et al. (1997) and Siegler and Jenkins referred to as a "critical slowing down." We found that children often paused when responding to the request to explain their solution, but sometimes the pauses were very long. We decided to count any pause that lasted more than 3 s as a long pause. We chose this pause length because pauses that were shorter may have stemmed from a physical (e.g., swallow, throat clearing, deep breath)—rather than a mental—cause and we wanted to ignore pauses that did not capture a critical slowing down.

Ten of the children's full sets of explanations were coded by two judges to establish reliability. Percentage agreements for each index were 91% for false starts and self-repairs, 95% for metacognitive comments, 92% for deletions, and 87% for long pauses. Cohen's kappa across all categories was .83.

Results

Analyses of the 98 students who had a complete set of data for analysis were completed in three stages. First, we examined possible effects that could be attributed to the various instructional interventions. Second, we classified children on the basis of the sort of progress they made between the initial assessment of their understanding and the completion of their participation in the study. General features of students' problem-solving performance that were unrelated to verbal imprecision are discussed in this second subsection. Third, we looked for differences in verbal imprecision at the time of students' initial assessment. In each of these stages, we looked for features of students and their behaviors that potentially could be used to predict and understand the development of success in solving gear-movement problems.

Effects of the Instructional Interventions

Initially, we conducted an analysis to determine whether the children in the different instructional conditions began on equal footing. In particular, we conducted an analysis of variance (ANOVA) on the number of correctly solved problems by children in the five instructional conditions. We found a significant difference across groups, $F(4, 93) = 4.34$, $p = .003$, indicating that the children in the different instructional conditions did not perform equally at the time of the pretest. We then conducted Tukey's honestly significant difference post hoc comparisons to pinpoint these initial differences in problem-solving performance (all reported post hoc tests had p values $\leq .05$). We found that the children in the verbal-principle-alone condition performed significantly lower than the children in three of the other instructional conditions (manipulation-only, consider-all-gears, and verbal-principle-plus-picture-plus-manipulation conditions) at the time of the pretest. Mean differences in initial performance ranged from 1.09 to 1.29 (out of a possible 7).

Although the differences in initial performance were significant, we were not certain that the differences were important. We had hoped that the children in each condition were on relatively equal footing at the time of the pretest so that we could attribute any differences in outcome, across conditions, to intervening instruction and not to already identifiable superiority in performance. Thus, we conducted a test of whether initial differences in performance were maintained from pretest to posttest or predisposed the children to react differently to instruction. In particular, we examined whether children in any of the instructional conditions had significantly greater gains in the number of problems solved correctly from the pretest to the posttest. We found that instructional condition could not significantly predict either the number of newly solved problems, $F(4, 93) = 2.20$, *ns,* or the total number of posttest problems solved correctly, $F(4, 93) = 1.84$, *ns.* These analyses suggest that none of the instructional conditions were better or worse than the others in fostering new learning. Because we did not find differences in learning that could be attributed to instructional condition, the remaining analyses were conducted without attention to instructional condition.

Classification Based on Performance Patterns

Four major performance patterns, based on changes in performance from the initial to the final session, emerged for the 98 students who initially solved some problems incorrectly. The first group of students ($n = 24$) solved each of the seven problems correctly by the end of the follow-up session. We classified these students as full learners. The second group of students ($n = 44$) solved more of the problems correctly by the end of the follow-up session than they had in the initial session but never came to solve all of the problems correctly. We classified these students as partial learners. The third group of students ($n = 24$) answered exactly the same number of problems correctly on both the pre- and posttests throughout the initial and follow-up sessions. We classified these students as staying the same (at times referred to as "nonlearners" for grammatical ease). The fourth group of students ($n = 6$) solved fewer problems correctly on the follow-up posttest than they had on the initial pretest. We initially classified these students as regressing in their understanding. However, during subsequent analyses, we found that these students could not be classified as one group because we found large variation across individuals. For example, some of these students behaved much like the nonlearners—indeed these students had not learned—but other students became much more confused (e.g., they came up with bizarre explanations that had not been a part of their earlier repertoires). Given our lack of confidence that these children actually performed similarly to each other and the small number of children whom we initially classified as regressing, we chose not to include these students in the remaining analyses. Thus, all remaining reported analyses were limited to the full learners, partial learners, and nonlearners.

The first question we asked about the different groups of students was whether initial understanding, as measured by the number of problems initially solved correctly, would predict the pattern of learning eventually achieved. We asked this because it was quite plausible that the students who eventually succeeded on our tasks

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were those who came in knowing the most. In other words, this analysis was conducted to examine whether any group had a significant advantage over the other groups of students when they began their participation in this study. To explore this issue, we divided the students on the basis of the categories of performance patterns (i.e., full learners, partial learners, and nonlearners) and examined whether we could find reliable differences in their initial performances.

The full learners initially answered an average of 3.76 ($SD = 0.83$) problems correctly, the partial learners answered an average of 3.14 ($SD = 1.30$) problems correctly, and the nonlearners answered an average of 3.63 ($SD = 1.35$) problems correctly. A one-way ANOVA revealed no significant differences among the three groups on the number of problems initially answered correctly, $F(2, 89) = 2.50$, *ns*.

Note that, by definition, the groups differed in their performance at the end of the follow-up session. In particular, the mean number of additional problems answered correctly was 2.80 for the full learners, 2.23 for the partial learners, and 0 for the nonlearners. As expected, the one-way ANOVA indicated a main effect for group on the number of new problems solved correctly by the end of the experiment, $F(2, 89) = 55.69$, $p < .001$. A Tukey post hoc analysis revealed that the students in each of the three learning-outcome groups differed significantly from the students in each of the other learning-outcome groups on the number of new problems solved correctly. This analysis confirmed that the three categories of patterns of performance were indeed significantly different from each other.

The second general feature that may have been related to problem-solving performance was gender, given the large attention to gender differences in science and mathematics (e.g., Beller & Gafni, 1996). Thus, we examined whether gender was significantly related to performance outcome. We found that the numbers of girls and boys did not differ significantly among the three performance-outcome categories, $\chi^2(2, N = 92) = 4.00$, *ns*.

Verbal Imprecision

In this section, first we report analyses for each of the measures of verbal imprecision. These analyses were conducted to examine differences between students who displayed different performance patterns. We report each of these analyses separately to provide an in-depth look at the behavior of these variables across groups of children. Second, we present analyses that allowed us to examine the ways in which these measures are interrelated. Finally, we present analyses that address lingering concerns about the potential role that verbal imprecision might play in producing cognitive change.

The four indexes of verbal imprecision. Descriptive statistics for each of the four indexes are presented in Table 3. For each measure of verbal imprecision, we used one-way ANOVAs to examine differences across the types of learners, and in each case, significant effects were found, $Fs(2, 89) \geq 3.20$, $ps \leq .05$. The effects of each one-way ANOVA were tested with Tukey post hoc analyses.

The full learners produced the most false starts and self-repairs, compared with the partial learners and the nonlearners. The full learners produced significantly more false starts and self-repairs than the partial learners and the nonlearners, who did not differ from each other.

The full learners produced significantly more metacognitive comments than both the partial learners and the nonlearners. The partial learners and the nonlearners did not differ significantly from each other in terms of the number of metacognitive comments they produced.

The full learners and the partial learners were significantly more likely to delete constituents than were the nonlearners. The full learners and the partial learners did not differ significantly from each other in terms of the number of deletions coded in their responses.

The full learners produced more long pauses than the nonlearners. The partial learners were not significantly different from the full learners or the nonlearners in terms of the number of long pauses they produced.

Potential mitigating factor: Verbosity. Although each of the four measures of verbal imprecision that we examined was related to learning outcomes, we realized that one or more of these measures might have been epiphenomenal of just being verbose. In other words, it was possible that children who learned more also talked more, potentially because they were more verbal than the other children. This initial verbosity may have allowed for the production of relatively larger numbers of false starts, and so forth, as compared with the children who talked less. We raised this issue earlier in relation to prior work (e.g., Hosenfeld et al., 1997; Siegler & Jenkins, 1989), which had noted extended response times among children in transition but had not specified why response times were longer. If children who are wordy tend to be in transition more often relative to children who are succinct, the extended response times noted by other investigators may simply be a function of being very verbal and very talkative.

It was also possible that we might find the opposite pattern:

Table 3
Mean Number and Standard Deviations of Instances of Verbal Imprecision Produced by Children With Different Learning Outcomes

Learning-outcome group	False starts and self-repairs		Metacognitive comments		Deletions		Long pauses	
	M	*SD*	*M*	*SD*	*M*	*SD*	*M*	*SD*
Full learners	6.04	4.85	2.96	2.58	5.25	3.93	2.83	3.81
Partial learners	4.30	2.75	1.71	3.09	4.55	3.10	1.64	2.83
Nonlearners	2.67	1.69	1.13	1.23	2.38	2.23	0.96	1.71

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Children who spoke relatively little might have been in transition more than children who spoke a lot. This was possible given Graham and Perry's (1993) finding that children who produced vague responses were significantly more likely to have been in transition than children who produced explicit responses. Although Graham and Perry did not report the number of words spoken by the vague and explicit children, we strongly suspect that the vague children used fewer words than the explicit children.

Thus, our next analysis examined whether the number of words that children produced across the seven problems predicted learning outcomes. On average, the full learners spoke more words in response to the experimenter's question regarding how they solved the problem than the partial learners, who, in turn, used more words than the nonlearners (*M*s = 277 words, 252 words, and 204 words, respectively). However, these differences were not significant, $F(2, 89) = 2.73$, *ns.*

Relations among the indexes of verbal imprecision. Each of the indexes of verbal imprecision was positively related to each other. The correlation matrix that displays the relations among these variables is shown in Table 4. These indexes were at times significantly related to each other, but the magnitude of these relations was not large, except for the relation between long pauses and false starts, $r(91) = .34$, $p < .01$. When the types of verbal imprecision occurred together, we most often found that metacognitive comments were produced with one of the other three types of verbal imprecision. Indeed, the production of metacognitive comments was significantly related to the production of each of the other three types of verbal imprecision (see Table 4). At the other end of the spectrum, deletions were the least likely to be produced by children who also produced the other types of verbal imprecision; deletions correlated significantly only with metacognitive comments (see Table 4).

We followed the correlations with a principal-components analysis. We did this to determine whether these four measures, which each differentiated among the learning-outcome groups, should rightfully be considered as a single contributing factor or as multiple contributing factors to learning outcomes. We found that the four measures of verbal imprecision each loaded highly on the first principal component (eigenvalue = 1.65), and the remaining principal components had eigenvalues below 1.00. This suggested that a single component representing each of the four measures of verbal imprecision could be used to predict learning outcomes.

We devised our composite measure of imprecision by adding all four measures together. This was justified on the grounds that each of the variables loaded approximately equally on the first principal component (component loadings were .69, .69, .45, and .69 for false starts, metacognitive comments, deletions, and long pauses, respectively).

Table 4
Correlations Among Indexes of Verbal Imprecision

Index	1	2	3	4
1. False starts and self-repairs	—			
2. Metacognitive comments	.26*	—		
3. Deletions	.07	.24*	—	
4. Long pauses	.34***	.24*	.11	—

Note. $df = 91$.
* $p \leq .05$. *** $p \leq .01$.

We next conducted a regression analysis to examine whether the variables present before any learning took place could explain eventual learning outcomes. We entered the following variables into our regression equation: age, gender, total imprecision (i.e., the sum total of false starts, metacognitive comments, deletions, and long pauses), number of pretest problems solved correctly, and instructional condition. These five variables predicted a significant amount of variance in learning outcomes, $R^2 = .30$, $p < .001$. Furthermore, we found that total imprecision was the only variable that could not be dropped from the model without losing predictability; if any of the other variables were dropped, we would not have reduced the fit of the model.[1] In other words, the composite measure of verbal imprecision significantly predicted learning outcomes, and the other variables did not add significantly to the variability in learning outcomes.

Possible role of verbal imprecision in producing new understanding. Thus far, we have treated learning-outcome data categorically. We chose to do this because of the conceptual differences between, for example, no changes in performance and solving everything correctly. However, we could also treat these data continuously. In doing so, we recognize the potential continuum of progress in learning and in the degree of verbal imprecision.[2]

To address this issue, we computed correlations between measures of performance and imprecision, thereby anticipating the potentially changing status of imprecision along with changes in understanding. These correlations are shown in Table 5. At the time of the pretest, the only measure of verbal imprecision that was significantly related to number of problems solved correctly was deletions. Moreover, this relation was negative, $r(91) = -.23$, $p = .028$, indicating that the more problems solved correctly, the fewer deletions produced. At the time of the posttest, two measures of verbal imprecision, metacognitive comments and long pauses, were significantly and positively related to the number of problems solved correctly. Again, as was true at the time of the pretest, although the correlations were significant, they were modest. We take this finding to suggest that the number of problems solved correctly is not the best indicator of understanding and that, at least for understanding how gears move, developing understanding is more accurately considered categorical than incremental.

An important postscript here concerns whether some types of verbal imprecision might have been more prevalent in the children from one of the instructional conditions, and other types in other conditions, thus masking any true instructional effects. We found no differences between instructional conditions in the production of deletions, $F(4, 87) = 0.86$, *ns;* false starts, $F(4, 87) = 0.25$, *ns;* long pauses, $F(4, 87) = 1.25$, *ns;* or metacognitive comments, $F(4, 87) = 1.00$, *ns.* These analyses provided further evidence that the initial differences in the children among the five instructional conditions were minor. Furthermore, because these differences were minor, and in most cases insignificant, we could not conclude

[1] We note that both gender and instructional condition were entered as categorical variables and the others were entered as continuous variables.

[2] We thank a thoughtful anonymous reviewer for raising this point and Patricia Bauer for suggesting the analysis to examine this issue.

Table 5
Correlations Between Measures of Verbal Imprecision and Number of Problems Solved Correctly at the Time of the Pretest and the Posttest

Measure	Pretest	Posttest
False starts and self-repairs	−.04	.19
Metacognitive comments	.10	.21*
Deletions	−.23*	.13
Long pauses	−.10	.21*

Note. $df = 91$.
* $p \leq .05$.

that initial differences might have interacted with information presented in instructional conditions, and again we could not conclude that the instructional conditions were responsible for differential outcomes.

Imprecision's link to transition. Next, we examined whether children's imprecision was linked to their transitional status. Although our suspicion was that children would become more articulate after learning, it was also possible that children would not change. In other words, it was possible that children who were, for example, prone to produce metacognitive comments before learning were just as prone to producing them after learning. To look at this issue more carefully, we transcribed and coded those sessions when the full learners displayed their initial successful problem solving. In these sessions, if verbal imprecision was linked to transition, we would have expected to find few instances of verbal imprecision because these children no longer needed to accomplish a transition (with respect to the concept they were working on). However, if verbal imprecision captured individual differences among children, we would have expected no significant change in the production of verbal imprecision after we witnessed a change in understanding.

Using paired *t* tests, we found significant decreases in all measures of verbal imprecision for the full learners. These data are displayed in Table 6. We found that when no transition was to be made (i.e., after a successful solution had been achieved), children produced very few dysfluencies.

We also realized that if imprecision was a true mark of transition and relative precision was a mark of relative stability, we should have found comparable production of verbal imprecision for the nonlearners, the children who came to the study knowing how to solve the problems, and the full learners after they had learned. Using a multivariate analysis of variance procedure, we found no differences between these groups in the production of types of verbal imprecision, $F(2, 51) = 0.82$, *ns*.

Discussion

Effects of the Instructional Interventions

The different instructional conditions had comparable effects on learning. This result was somewhat surprising because we expected that at least some direction or guidance would be necessary for students to demonstrate improvement. Given adults' difficulty with these problems (Perry & Elder, 1997; Schwartz, 1995), we did not expect that the manipulation-only instruction would be as useful for promoting cognitive change as, for example, the verbal-principle-plus-picture-plus-manipulation instruction. The fact that no significant differences were found across instructional conditions leads to the inference that repeated exposure to gear-movement problems, especially when attention is called to these problems, may be sufficient to stimulate cognitive development. Unfortunately, it is difficult to test whether this is the case because it is difficult to imagine a scenario in which the problems are given but the learner does not realize that this is the focus of the investigation, so that no special attention is called to the problems. In any case, it is apparent that repeated exposure to these problems is sufficient to lead to improvement in performance for certain students. Next, we turn to the issue of why some students, and not others, improved in their performance.

Indexes of Verbal Imprecision as Indicators of Transition

All four types of verbal imprecision examined in this study successfully predicted transitional knowledge about gear movement. In other words, when we looked at how students verbally expressed their problem-solving procedures, we could detect—from their verbal utterances—that some students responded to the problems differently. Note that we could not make this inference from the number of problems they initially solved correctly, their age, or their sex.

Although all four indexes of verbal imprecision loaded on the same principal component, their patterns of production were not identical. We suspect that an examination of the nuances in the production of distinct types of verbal imprecision potentially may be revealing about how knowledge is organized during times of transition. We add the caveat that further investigation is needed to confirm our understanding about how these indexes reveal subtle changes in cognitive development.

Recall that univariate analyses revealed that the full learners produced significantly more false starts and self-repairs and metacognitive comments than both the partial learners and the nonlearners. The sort of backtracking and restarting that characterize false starts and self-repairs may indicate a difficulty in accessing just-used problem-solving attempts. In other words, when children are verbally imprecise by starting their explanations over and revising what they just said about how they had just solved that problem, it is easy to get the sense that they really could not readily conjure up how they had just solved that problem. Also, when we

Table 6
Production of Verbal Imprecision at the Pretest and at the Time of Successful Problem Solving

Measure	Mean amount: Pretest	Mean amount: Successful session	$t(22)$
False starts and self-repairs	6.04	3.91	2.37**
Deletions	5.25	1.96	3.72****
Long pauses	2.83	0.70	3.26****
Metacognitive comments	2.96	1.17	3.39****

Note. One child was omitted from this analysis because the audiotaped portion of her posttest was defective.
** $p \leq .03$. **** $p \leq .004$.

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reviewed the videotapes of these children, these children gave the impression that they were not satisfied with their answers and they were in search of a better way to deal with these problems. Given the data and impressions when watching these children, we suspect that the full learners were in the process of rejecting old, presumably inefficient or ineffective, problem-solving approaches.

In further understanding the significance of the production of metacognitive comments and false starts and self-repairs, we note that these types of verbal imprecision were significantly related to each other. Although the production of metacognitive comments was also correlated significantly with the other types of imprecision, the pattern of learning was comparable for these two types (i.e., metacognitive comments and false starts and self-repairs) and was different from the other two types of verbal imprecision (i.e., deletions and long pauses). We take from this that confusion about how to solve the problems, as indexed by metacognitive comments, and the difficulty in accessing just-used problem-solving approaches, as indexed by false starts and self-repairs, tend to co-occur because our participants might have been compelled to admit confusion when they were in the process of rejecting previously used approaches.

Full learners and partial learners did not differ significantly in terms of their production of deletions. Both groups of participants produced significantly more of these types of verbal imprecision than did nonlearners. We suspect that production of deletions successfully characterized both partial learners and full learners because both groups were working toward adopting new approaches and applying already known and successful approaches to new problems. This stands in contrast to replacing or rejecting old approaches, which apparently happened for the full learners (as evidenced by their significant use of false starts and self-repairs) but not for the other groups of participants. Thus, we have at least some evidence that adopting a new approach and rejecting an old one may be independent, and ordered, processes of knowledge change.

The final type of verbal imprecision that we investigated, long pauses, distinguished full learners from nonlearners. The pattern of evidence from this investigation suggests that long pauses probably signal search attempts. We say this because we imagine that stopping many times, for 3 or more seconds, during an explanation of how you just solved the problem probably means that you are searching among, and perhaps even evaluating, multiple available problem-solving approaches. The nonlearners were not likely to do this.

Thus, we suggest something that takes into account what Hosenfeld et al. (1997) suggested—that critical slowing down can be attributed to behaviors no longer being automatic—and what Siegler and Jenkins (1989) suggested—conflict. We make both of these suggestions because if a learner must pause for more than 3 s over and over again, and this learner is also likely to restart or self-correct, then the learner could be taking time to access an approach and is probably making decisions about the problem-solving approach at the time of the verbal production.

It is possible that this sort of knowledge can prove fruitful to teachers, tutors, and peers when they need to evaluate a learner's current understanding and potential to learn. For example, in informal discussions with teachers, we found that the teachers believed that students who muddled their responses were the students who were the least likely to make progress or grasp what the teacher was trying to communicate. Sharing the results of this investigation with educators could prove valuable, minimally in that teachers may gain an appreciation and a decrease in frustration when they witness verbal imprecision in their students and maximally in that teachers would use this information to optimize the match between students' instructional needs and their own instructional output. Additional research is clearly needed if we are to make good use of this information in classroom settings. In the meantime, and at the very least, the results from this investigation provide knowledge about the different ways that verbal imprecision may take form and what these forms of imprecision may mean about processes of knowledge change.

In sum, we have identified different types of verbal imprecision, which appear to tap into different aspects of knowledge change processes. The patterns of producing these types of verbal imprecision among full learners, partial learners, and nonlearners provide further insight about how knowledge is organized at different points in the learning process. Thus, when it comes to evaluating a learner's understanding of a concept, it is important to keep in mind that it is not enough to know what was said but also how it was said.

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