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Making Children Gesture Brings Out Implicit Knowledge and Leads to Learning

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Speakers routinely gesture with their hands when they talk, and those gestures often convey information not found anywhere in their speech. This information is typically not consciously accessible, yet it provides an early sign that the speaker is ready to learn a particular task (S. Goldin-Meadow, 2003). In this sense, the unwitting gestures that speakers produce reveal their implicit knowledge. But what if a learner was forced to gesture? Would those elicited gestures also reveal implicit knowledge and, in so doing, enhance learning? To address these questions, the authors told children to gesture while explaining their solutions to novel math problems and examined the effect of this manipulation on the expression of implicit knowledge in gesture and on learning. The authors found that, when told to gesture, children who were unable to solve the math problems often added new and correct problem-solving strategies, expressed only in gesture, to their repertoires. The authors also found that when these children were given instruction on the math problems later, they were more likely to succeed on the problems than children told not to gesture. Telling children to gesture thus encourages them to convey previously unexpressed, implicit ideas, which, in turn, makes them receptive to instruction that leads to learning.

Keywords: embodied cognition, gesture, implicit knowledge, learning, mathematical equivalence

Learners are often able to perform a task successfully without being able to describe what they did to succeed (e.g., Siegler & Stern, 1998). These learners are said to have implicit rather than explicit knowledge of the task—knowledge that is not accessible to speech but is nevertheless evident in other behaviors. In previous work, we have shown that the spontaneous gestures speakers produce when they talk can convey information not found anywhere in their spoken repertoires (Goldin-Meadow, 2003; Goldin-Meadow, Alibali, & Church, 1993). Moreover, the information that speakers convey uniquely in gesture on a task provides an early sign that those speakers are ready to learn the task (Church & Goldin-Meadow, 1986; Perry, Church, & Goldin-Meadow, 1988; Perry & Elder, 1997; Pine, Lufkin, & Messer, 2004). Thus, speakers' gestures can reveal knowledge that they have but cannot yet articulate: in other words, implicit knowledge. In this study, we explored whether forcing speakers to gesture encourages them to reveal knowledge that they have not previously expressed, which, in turn, prepares them for learning.

Tapping Implicit Knowledge

How can one tell when a learner has implicit knowledge? As mentioned earlier, learners can sometimes successfully perform a task without being able to articulate how they accomplished the task (Berry & Broadbent, 1988; Karmiloff-Smith, 1986; Reber, 1989). For example, Reber and Kotovsky (1997) had adults sit in front of a computer screen on which five boxes and five balls were displayed. The task was to remove each of the balls from its box, but the adults were not told the rule for moving the balls (the rightmost ball could always move; other balls could be moved only if the ball immediately to its right was in its box and all other balls to the right were out of their boxes). The adults learned to solve the puzzle, but many were unable to articulate what they had done to succeed.

In cases of this sort, the learner's correct performance signals an implicit understanding of the task. But what about cases in which learners cannot perform the task correctly? Might they nevertheless have accurate implicit knowledge, and, if so, how would anyone know? One way to at least partially access implicit knowledge is to include a judgment component in the testing situation. For example, Bowers, Regehr, Balthazard, and Parker (1990) asked adults to figure out the word associated with a triad of words (e.g., to produce the common associate *card* when given *playing*, *credit*, and *report*). Adults were presented with two triads at a time, one that had an associate and one that did not, and were asked to find the associate for the triad that could be solved. If they could not solve the puzzle, they were asked to judge which triad was likely to be solvable (i.e., which was likely to have an associate).

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The interesting finding was that, more often than not, adults correctly identified the triad that was solvable even though they could not arrive at the solution. In other words, they had implicit knowledge that the triad was solvable, akin to a feeling of knowing in memory (Koriat, 1993) or insight (Metcalfe, 1986) problems. Similar judgment tasks have also been used to reveal implicit knowledge in children. For example, Siegler and Crowley (1994) asked 9-year-old children to judge which of two strategies was a smarter way to play tic-tac-toe. They found that children who did not yet use the adult forking strategy nevertheless judged it to be smarter than their own win–block strategy.

Although judgment tasks are able to reveal partial knowledge that learners have but cannot articulate, the tasks themselves are necessarily constrained—the experimenter selects a set of alternatives (e.g., the particular set of word triads) and asks learners to make judgments about these particular choices. For the most part, these judgment tasks indicate that a learner has partial knowledge but not necessarily what that knowledge is. One could address this concern by asking adults to think aloud while solving problems. Fleck and Weisberg (2004) did just that and found that verbal protocols on insight problems revealed the particular steps that the adults took to arrive at the solution—in other words, partial knowledge prior to successful performance rather than a sudden shift to successful performance. But verbal protocols such as Fleck and Weisberg's (2004), although informative, have the disadvantage that the knowledge they reveal cannot, by definition, be implicit because it is explicitly displayed in speech. In the current work, we turn to the gestures that speakers produce when they talk as an alternative way to explore implicit knowledge in individuals who cannot yet perform a task successfully. Gesture not only has the potential to reveal that a speaker has implicit knowledge but can also reveal what that implicit knowledge is.

Spontaneous Gesturing Taps Implicit Knowledge

Many researchers have argued that the gestures speakers produce when they talk convey substantive information and, as such, provide insight into a speaker's mental representations (Goldin-Meadow, 2003; Kendon, 1980; McNeill, 1985, 1987, 1992). For example, McNeill (1987) found that speakers use hand gestures to depict both concrete images (e.g., the actions or attributes of cartoon characters) and abstract concepts (e.g., mathematical concepts, such as quotients, factors, and even limits in calculus). Although the gestures that accompany speech may appear to be meaningless hand waving, those gestures do, in fact, convey information and are produced in a wide range of discourse situations: in spontaneous conversations (Kendon, 1980), in narrative expositions (McNeill, 1992), in descriptions of objects and actions (Goldin-Meadow, McNeill, & Singleton, 1996), and in explanations both in the classroom (Crowder & Newman, 1993) and in one-on-one tutorial situations (Church & Goldin-Meadow, 1986; Evans & Rubin, 1979; Perry et al., 1988). Meanings can be assigned to the gestures produced in these situations, and independent observers tend to assign the same meaning to the same gesture (Goldin-Meadow, 2003).

More important with respect to implicit knowledge, speakers often convey information in their gestures that is not expressed in their speech. For example, Church and Goldin-Meadow (1986) observed children who were nonconservers on a Piagetian conservation task. Each child was first shown two rows containing the same number of checkers and was asked to verify that the rows had the same number. The experimenter then spread out the checkers in one row, leaving the second row unchanged, and asked the child whether the transformed row had the same or a different number of checkers as the untransformed row. All nonconserving children said "different" and justified their responses accordingly, saying, for example, "It's different because you moved them." However, some nonconserving children conveyed correct explanations in gesture at a time when they consistently gave incorrect answers and incorrect explanations in speech. For example, while saying that the number of checkers was different because "you moved them," one child moved a pointing finger from the first checker in the transformed row to the first checker in the untransformed row and then from the second checker in the transformed row to the second checker in the untransformed row and so on (Church & Goldin-Meadow, 1986). Although not explicitly verbalizing the one-to-one correspondence between the checkers in the two rows, the child displayed an implicit awareness of the alignment in his gestures.

As another example, third and fourth grade American children are typically unable to solve mathematical equivalence problems of the following type: $6 + 4 + 5 = \_\_ + 5$. They frequently put 15 in the blank, presumably having added the 6, 4, and 5 on the left side of the equation, or they put 20 in the blank, having added all four numbers in the problem. When asked to describe how she solved this problem, one child who had put 20 in the blank said that she had added all of the numbers in the problem. But, at the same time, she gestured with her index and middle fingers extended in a V shape at the 6 and 4 and then pointed at the blank, effectively grouping the two numbers that should be added to arrive at the correct answer (Perry et al., 1988). Although she did not explicitly mention grouping, this child displayed an implicit awareness of the principle in her gestures.

It is important to note that the information that learners express in gesture and not in speech is often unique to gesture: That is, it is not found anywhere in the child's speech (Alibali & Goldin-Meadow, 1993; Goldin-Meadow et al., 1993; Goldin-Meadow & Alibali, 1995). For example, the child who conveyed the grouping principle in her gestures did not convey grouping in her speech on any of the problems she solved. Thus, the information was uniquely expressed in gesture. Indeed, when children generate new strategies for solving problems, they often begin by expressing these new strategies uniquely in gesture, particularly when the strategies are generated in the absence of direct instruction (Alibali, 1999).

Although not accessible to speech, the knowledge conveyed uniquely in gesture can be accessed by tasks traditionally used to tap implicit knowledge (e.g., Acredolo & O'Connor, 1991; Horobin & Acredolo, 1989; Siegler & Crowley, 1994). Garber, Alibali, and Goldin-Meadow (1998) used a judgment task to determine whether children have access to the information that they express uniquely in gesture. They gave children problems of the $6 + 4 + 5 = \_\_ + 5$ type and asked them to rate the acceptability of a series of potential answers. That is, the children were asked, in sequence, whether 10, 15, and 20 were each an acceptable answer to the problem. It is interesting that the children were quite happy to rate several answers as acceptable solutions to the problem (which suggests an incomplete understanding of mathematical equations at the very least). Not surprisingly, children rated answers derived from strategies that they expressed uniquely in gesture (e.g., 10 in the above example, the answer derived from the gestured grouping strategy) lower than they rated answers derived from strategies that they expressed in speech (20, derived from the spoken add-all-numbers strategy). However, the interesting finding is that children rated answers derived from strategies that they expressed uniquely in gesture (10, derived from the grouping strategy expressed in gesture) higher than they rated answers derived from strategies that they did not express in either speech or gesture (15, derived from the unexpressed add-numbers-to-equal-sign strategy). Thus, knowledge expressed uniquely in gesture was accessible to the children, as demonstrated by the types of judgment tasks typically used to tap implicit knowledge in adults (e.g., Bowers et al., 1990).

The final piece of evidence that gesture can tap implicit knowledge is that children who convey information in gesture and not in speech when explaining an incorrect solution to a problem are particularly likely to profit from instruction in that task. Using a conservation task, Church and Goldin-Meadow (1986) found that children who often produced gestures conveying different information from that conveyed in their speech were significantly more likely to profit from instruction in conservation than were children who produced few such gestures. Perry et al. (1988) replicated this phenomenon in math, showing that the proportion of problems on which children produced gestures conveying different information from that conveyed in their speech was a good predictor of how ready the children were to learn how to solve that type of problem (see also Perry & Elder, 1997, who found the same effect in adults). Moreover, Church and Goldin-Meadow (1986) found that the strategies children expressed in gesture prior to training on the conservation task were precisely the strategies that the children produced in speech after training. Thus, the knowledge learners convey uniquely in gesture can foreshadow their next developmental step. Taken together, the above evidence suggests that the spontaneous gestures that unsuccessful learners produce on a task can reflect the implicit steps that learners take on the road to mastering the task.

Eliciting Implicit Knowledge

Asking learners to talk while solving a problem offers a window onto their changing thoughts about the problem (Ericsson & Simon, 1993). But talking can do more than reveal steps on the path to learning: It can, at times, facilitate the learning itself (in, e.g., analytical problem solving, Schooler, Ohlsson, & Brooks, 1993; or memory for verbal statements, Schooler & Engstler-Schooler, 1990). In other words, the task of expressing explicit knowledge can facilitate changes in that knowledge.

The question we address in this study is whether engaging in actions that are known to reflect implicit knowledge also facilitates learning. As noted earlier, many studies have shown that learners often implicitly know more about a problem than they reveal in their unsuccessful attempts at solving the problem. But, as far as we know, no studies have encouraged learners to do the things that allow for the expression of implicit knowledge so that the impact of this knowledge on subsequent learning could be explored—in large part because it is difficult, by definition, to get learners to express implicit knowledge. But learners can be asked to gesture, which is often a vehicle for implicit knowledge. We can ask learners to gesture just as we can ask them to talk. We can then explore whether telling learners to gesture leads to an increase in implicit knowledge and paves the way for learning. We envision two possible outcomes.

On the one hand, making the act of gesturing explicit could fundamentally alter the link between gesture and implicit knowledge. If so, speakers who are forced to gesture would produce gestures that convey the same information as their speech and thus not reveal any implicit knowledge. On the other hand, even when encouraged to gesture, speakers may not be able to directly control what they do with their hands. Someone can be told to gesture, and obedient speakers will concentrate on making sure that their hands are in motion, but they may not be able to explicitly direct the particular movements they make with their hands in a step-by-step fashion. If so, their elicited hand motions might still have the potential to reveal implicit knowledge. Encouraging gesture might then be an excellent way of forcing speakers to reveal whatever implicit knowledge they have. We explored these possibilities in Study 1.

Study 1

Our goal in Study 1 was to determine whether forcing speakers to gesture encourages them to express implicit knowledge. We asked children to solve two sets of six mathematical equivalence problems: the first with no instructions about gesturing (baseline) and the second with instructions to move their hands while explaining how they solved each problem, with instructions not to move their hands, or with no instructions (a between-subjects manipulation). We could then assess whether telling children to gesture affects the types of problem-solving strategies they express explicitly in speech and implicitly in gesture.

Method

Participants. Participants were 106 children (55 girls, 51 boys) tested individually at their schools in the Chicago area. Children were either in the latter part of third or the early part of fourth grade.

Baseline phase. Children were asked to solve six problems of the $6 + 3 + 7 = \_\_ + 7$ type on a chalkboard and to explain how they solved each problem to an experimenter. The experimenter wrote the first problem on the board, the child solved it, and then the experimenter asked the child to explain how he or she had arrived at the solution. This procedure was repeated until the child had explained all six problems. No mention was made of gesture during this phase of the study. The procedure was videotaped for later analysis of strategies produced in speech and/or gesture at baseline. To make the groups as comparable as possible, we eliminated the few children who solved any problems correctly from the study; thus the 106 children who were included in the study solved no problems correctly in the baseline set. Children were then randomly assigned to one of three groups, which determined the instructions they received during the manipulation phase.

Manipulation phase. Children were asked to solve and explain another six problems at the board. Children in the *told-to-gesture group* ($n = 33$) were asked to use their hands when they explained how they solved the problems; children in the *told-not-to-gesture group* ($n = 35$) were asked to keep their hands still when explaining their solutions; children in the *control group* ($n = 38$) were told to explain how they solved the problems with no mention of their hands. Children were reminded of these instructions throughout the manipulation phase. The procedure was videotaped for later analysis of strategies produced during manipulation; these strategies were compared with strategies produced at baseline.

Coding problem-solving strategies in speech and gesture. All of the children's speech and gestures were transcribed and coded according to a previously developed system (Perry et al., 1988). Only those gestures and spoken utterances that conveyed strategies for solving the problems were analyzed. Overall, children produced three strategies that led to correct answers and three that led to incorrect answers in speech and gesture (see Table 1).

One experimenter made two passes through the data, once coding speech and a second time coding gesture. The speech and gesture codes for the six explanations produced at baseline were then compared. A particular strategy type (e.g., equalizer, grouping) was classified as occurring *uniquely in gesture* if the child produced it in gesture and never in speech across the six problems. All other strategies that the child produced were classified as occurring in *speech*, with or without gesture; that is, the child produced the spoken strategy in speech and may or may not have produced that strategy in gesture as well.

Reliability was assessed by having a second experimenter independently code a random subset of the explanations. Agreement between coders was 98% ($n = 20$ children) for assigning strategy codes to speech and 96% ($n = 24$ children) for assigning strategy codes to gesture.

Results

Strategies produced during baseline. To ensure that the children in the three groups did not differ prior to the manipulation, we calculated the total number of different strategies each child produced in speech at baseline and found no significant differences, $F(2, 103) = 2.09$, $p = .13$: For the told-not-to-gesture group, $M = 1.71$, $SD = 0.46$; for the control group, $M = 1.50$, $SD = 0.51$; for the told-to-gesture group, $M = 1.51$, $SD = 0.51$. Of note, none of these spoken strategies were correct.

Of the 106 children, 67 gestured at baseline. Gesturers were equally distributed across groups, $\chi^2(2) = 1.00$, $p = .61$: Twenty of 35 children gestured in the told-not-to-gesture group, compared with 26 of 38 in the control group and 21 of 33 in the told-to-gesture group. Moreover, the groups did not differ in the mean number of problems on which they gestured, $F < 1$: For the told-not-to-gesture group, $M = 2.8$, $SD = 2.7$; for the control group, $M = 3.2$, $SD = 2.7$; for the told-to-gesture group, $M = 2.7$, $SD = 2.6$. Some children in each group produced strategies in gesture that they did not produce in speech; the mean number of these strategies did not differ across groups, $F < 1$. Eight produced a mean of 1.63 ($SD = 0.74$) strategies uniquely in gesture in the told-not-to-gesture group, 16 produced a mean of 1.75 ($SD = 0.68$) strategies in the control group, and 11 produced a mean of 1.91 ($SD = 1.04$) strategies in the told-to-gesture group. It is interesting to note that most of the strategies produced uniquely in gesture were correct: That is, 1.29 ($SD = 0.75$) were correct versus 0.49 ($SD = 0.61$) that were incorrect. Thus, although none of the children solved the math problems correctly and none expressed correct strategies in speech, some did have partial knowledge of how to solve the problems, which they expressed only in gesture.

Strategies maintained during manipulation. We asked first whether our manipulation instructions affected children's production of spoken strategies and found that they did not. The proportion of spoken strategies that children maintained from baseline was high and did not differ across groups, $F(2, 103) = 1.17$, $p = .31$: On average, 94% ($SD = 16\%$) of the spoken strategies that children in the told-not-to-gesture group produced during baseline were produced again during manipulation, compared with 93% ($SD = 17\%$) in the control group and 98% ($SD = 9\%$) in the told-to-gesture group.

Turning next to gesture, the first point to note is that children followed our instructions and differed in the mean number of problems on which they gestured during the manipulation, $F(2, 103) = 82.1$, $p < .0001$, $\eta_p^2 = .614$ (ps $< .0001$, Newman–Keuls): $M = 0.20$ ($SD = 0.53$) of the six problems in the told-not-to-

Table 1
Examples of Correct and Incorrect Strategies Children Produced in Speech and Gesture

Type of strategy	Speech	Gesture
Correct strategies		
Equalizer	"Both sides have to be the same."	Flat palm sweeps first under the left side of the problem and then under the right.
Equal-addends and grouping	"There's a 4 here and a 4 here; you can block them off and then add these two numbers to get the answer."	One flat palm covers the 4 on the left side of the problem and another covers the 4 on the right; V-hand indicates the 5 and 3 on the left side of the problem.
Add–subtract	"You can get the answer by adding up all of the numbers on the left side, then taking away the 4 on the right."	Pointing hand sweeps under the left side of the problem; hand points to the 4 on the right side and retracts; hand points to the blank.
Incorrect strategies		
Add all numbers	"I added all of them up."	Point at the 5, 3, left 4, right 4, and the blank.
Add to equal sign	"I added the 5, the 3, and the 4 to get the answer."	Point at the 5, 3, left 4, and the blank.
Carry	"I put the 5 there."	Point at the 5 and the blank.

Note. The strategies were used for mathematical equivalence problems of the following type: $5 + 3 + 4 = \_\_ + 4$. V-hand refers to the index and middle fingers extended in a V shape.

gesture group, $M = 2.5$ ($SD = 2.8$) in the control group, and $M = 5.8$ ($SD = 1.0$) in the told-to-gesture group (cf. $M = 2.9$, $SD = 2.6$, for the three groups at baseline). The gestures that the children produced when told to use their hands were comparable to those produced without instructions to gesture in that they could all be coded using the system developed for spontaneous gesture exemplified in Table 1. Children in the control group produced 33% (SD = 37%) of the gestured strategies that they produced at baseline again during the manipulation, compared with 32% (SD = 41%) in the told-to-gesture group, $F < 1$ (and, of course, none in the told-not-to-gesture group, who did not gesture during the manipulation). Only 1 child in the control group (and none in the other groups) switched a strategy produced uniquely in gesture at baseline into speech during the manipulation. The remaining strategies produced uniquely in gesture were dropped from the children's repertoires. In general, strategies produced uniquely in gesture were maintained less well than were spoken strategies (32% vs. 95%) and, in this sense, were less stable.

Strategies added during manipulation. Across the three groups, children added a mean number of 0.34 strategies ($SD = 0.72$) to their repertoires during the manipulation. It is interesting that 0.25 ($SD = 0.60$) of the added strategies were correct (the remaining 0.09, $SD = 0.29$, were incorrect), and nearly all, 0.32 ($SD = 0.70$), were expressed only in gesture and not in speech.

The three groups differed in the mean number of strategies added, $F(2, 103) = 12.38$, $p = .000015$, $\eta_p^2 = .194$. Children in the told-to-gesture group added significantly more strategies than did children in the control and told-not-to-gesture groups (ps $< .001$, Newman–Keuls), as illustrated in Figure 1. Even children who did not gesture spontaneously (i.e., who produced no gestures at baseline) added strategies uniquely in gesture when told to gesture ($M = 0.71$, $SD = 0.61$) and added no strategies when told not to gesture or when given no instructions regarding gesturing ($M = 0$, $SD = 0$, both groups).

In sum, telling children to move their hands when explaining how they solved the math problems encouraged them to convey previously unexpressed and correct ideas in gesture. Encouraging children to gesture had, in a sense, given them license to express whatever burgeoning thoughts they had about the problem. Typically in studies of implicit knowledge, participants are asked to choose between solutions and, without knowing why, the participant chooses the correct answer from a preselected set. In this study, the children themselves generated the correct strategies on their own. All it took was being told to gesture.

Study 2

In previous work, we have found that children who spontaneously express problem-solving strategies in gesture and not in speech are more open to instruction in mathematical equivalence than children who do not gesture in this way (Alibali & Goldin-Meadow, 1993; Perry et al., 1988). The present findings raise an obvious question: Does encouraging children to gesture, which (as Study 1 demonstrates) elicits new and correct strategies expressed uniquely in gesture, increase the likelihood that children will profit from instruction in mathematical equivalence? To address this

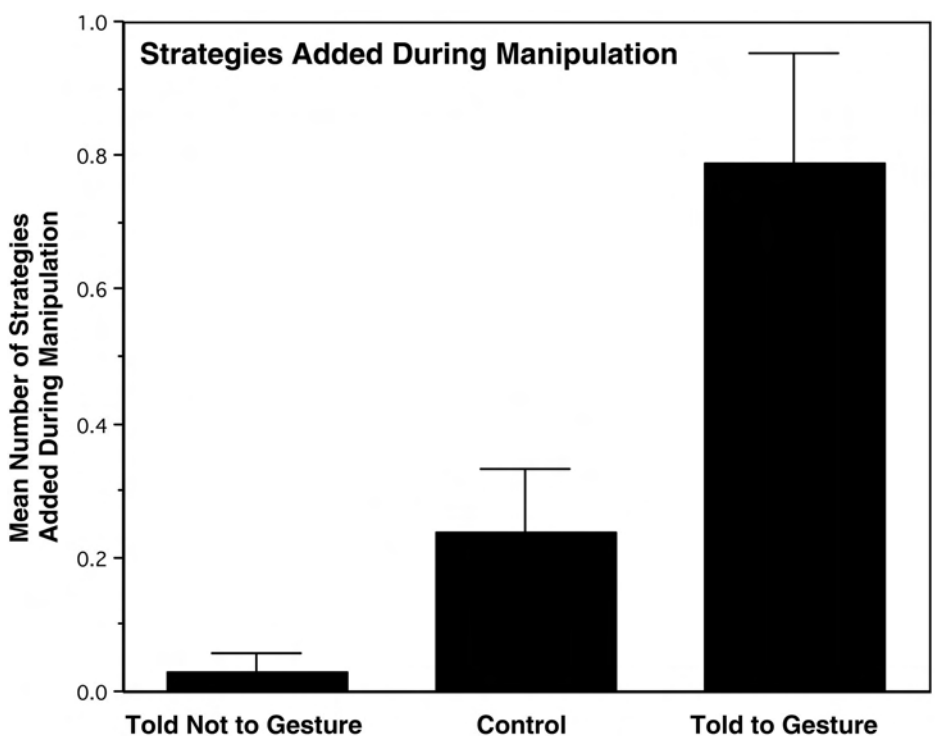

Figure 1. Mean number of strategies added during the manipulation phase of Study 1. Data are categorized according to the instructions the children received during manipulation (told not to gesture, control, told to gesture). Error bars represent standard errors.

question, we experimentally manipulated children's gestures as in Study 1 and added a lesson and posttest to assess learning.

Method

Participants. Participants were 70 children (37 girls, 33 boys), either in the latter part of third or the early part of fourth grade, tested individually at school. None had participated in Study 1.

Procedure. The design of Study 2 is shown in Figure 2. The *baseline phase* was identical to that of Study 1 except that children solved the six problems on paper at a desk before explaining the problems at the board; their performance on the paper-and-pencil test could then be used to measure improvement after the lesson. Children solved no baseline problems correctly.

The *manipulation phase* was also identical to that of Study 1, with the exception that children were randomly assigned to one of two (as opposed to three) groups: They were either *told to gesture* ($n = 36$) or *told not to gesture* ($n = 34$) while explaining their answers to the problems. We used these two groups because they were maximally distinct in terms of strategies added and because both involved giving instructions that drew children's attention to their hands.

After children solved and explained the six problems in the manipulation phase, they were given a lesson in mathematical equivalence. The experimenter put a problem on the board, solved it correctly, and told the child, while moving a flat palm first under the left side of the problem and then under the right side, that the way to solve the problem was to make both sides the same (the equalizer strategy produced in speech and in gesture; see Table 1). This procedure was repeated for six problems. Children neither solved nor explained the problems during the lesson. All they did was listen and watch. After the lesson, children were given a paper-and-pencil posttest containing the same types of problems as those given at baseline to assess the effect of the lesson.

Coding strategies. The strategies that the children produced during baseline and manipulation were coded using the same methods as used in Study 1.

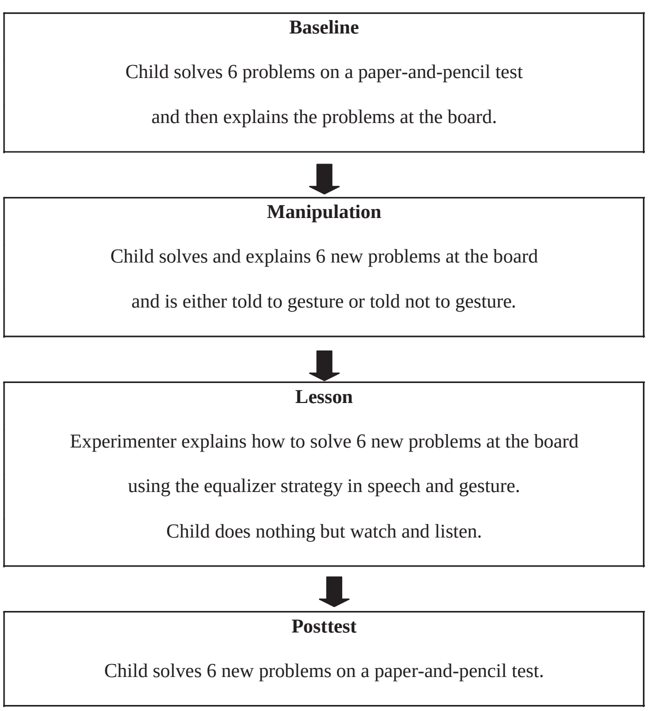

Figure 2. The procedure followed in Study 2.

Results

Strategies produced during baseline. Children in the two groups produced approximately the same number of different strategies in speech at baseline, $F < 1$: For the told-not-to-gesture group, $M = 1.18$, $SD = 0.39$; for the told-to-gesture group, $M = 1.22$, $SD = 0.48$.

Twenty-two of the 34 children in the told-not-to-gesture group gestured at baseline, as did 28 of the 36 children in the told-to-gesture group, $\chi^2(1) = 0.89$, $p = .34$. The two groups did not differ in the mean number of problems on which they gestured at baseline, $F < 1$: For the told-not-to-gesture group, $M = 2.9$, $SD = 2.6$; for the told-to-gesture group, $M = 3.4$, $SD = 2.5$. As in Study 1, some children in each group produced strategies in gesture that they did not produce in speech; the mean number of these strategies did not differ across groups, $F < 1$: Fourteen children produced a mean of 1.64 ($SD = 0.84$) strategies uniquely in gesture in the told-not-to-gesture group, and 13 produced a mean of 1.54 ($SD = 0.88$) in the told-to-gesture group. As in Study 1, most of the strategies produced uniquely in gesture were correct: An average of 1.22 ($SD = 0.80$) correct versus 0.37 ($SD = 0.56$) incorrect strategies were produced uniquely in gesture.

Strategies maintained during manipulation. The proportion of spoken strategies that the children maintained from baseline was high and did not differ across groups, $F < 1$: For the told-not-to-gesture group, $M = 93\%$, $SD = 22\%$; for the told-to-gesture group, $M = 86\%$, $SD = 33\%$.

Turning to gesture, we found that children followed our instructions and differed in the mean number of problems on which they gestured during the manipulation, $F(1, 68) = 565.6$, $p < .000001$, $\eta_p^2 = .893$: $M = 0.26$ ($SD = 0.61$) of the 6 problems in the told-not-to-gesture group and $M = 5.5$ ($SD = 1.1$) in the told-to-gesture group (compared with $M = 3.2$, $SD = 2.5$, for both groups at baseline). Children in the told-to-gesture group maintained 46% ($SD = 44\%$) of the gestured strategies they produced at baseline during manipulation; the remaining strategies were dropped from their repertoires. None of the children in either group switched strategies that they had produced uniquely in gesture at baseline into speech during the manipulation.

Strategies added during the manipulation. Across the groups, children added a mean number of 0.30 strategies ($SD = 0.60$) to their repertoires during the manipulation. As in Study 1, 0.24 ($SD = 0.55$) of the added strategies were correct (the remaining 0.06, $SD = 0.23$, were incorrect), and 0.21 ($SD = 0.54$) were expressed only in gesture and not in speech.

The two groups differed in the mean number of strategies added, $F(1, 68) = 21.58$, $p = .000016$, $\eta_p^2 = .241$. Children in the told-to-gesture group added strategies; children in the told-not-to-gesture group did not (see Figure 3, top panel). Even children who did not gesture spontaneously (i.e., they produced no gestures at baseline) added strategies when told to gesture ($M = 0.50$, $SD =$

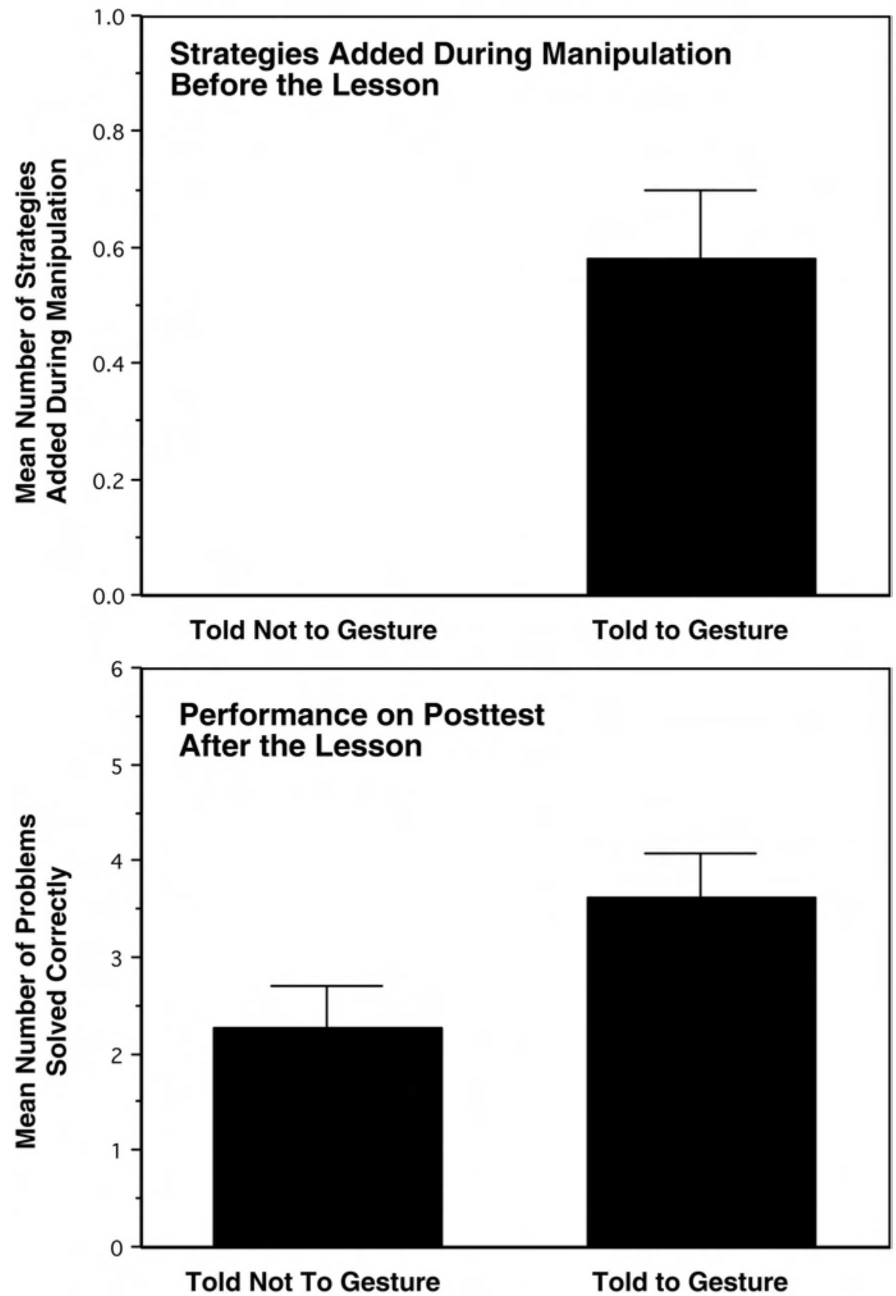

Figure 3. Mean number of strategies added during the manipulation phase of Study 2 (top panel) and mean number of problems solved correctly on the posttest after the lesson (bottom panel). Data in both graphs are categorized according to the instructions children received during manipulation (told not to gesture, told to gesture). Error bars represent standard errors.

0.76) and added no strategies when told not to gesture ($M = 0$, $SD = 0$).

Posttest performance. Did telling children to gesture before they received the math lesson make them more likely to profit from the lesson? To find out, we looked at the number of problems (out of six) solved correctly on the posttest after the lesson (see Figure 3, bottom panel; recall that no problems were solved correctly at baseline) and found a significant difference between groups, $F(1, 68) = 4.41$, $p < .04$, $\eta_p^2 = .061$: Children told to gesture prior to the lesson solved significantly more problems correctly at posttest than did children told not to gesture.

Was the relation between our gesture manipulation and posttest performance due to adding new strategies prior to the lesson? To the extent that adding new strategies underlies the effect that being told to gesture had on posttest performance, covarying out whether children added strategies should render the relation between the

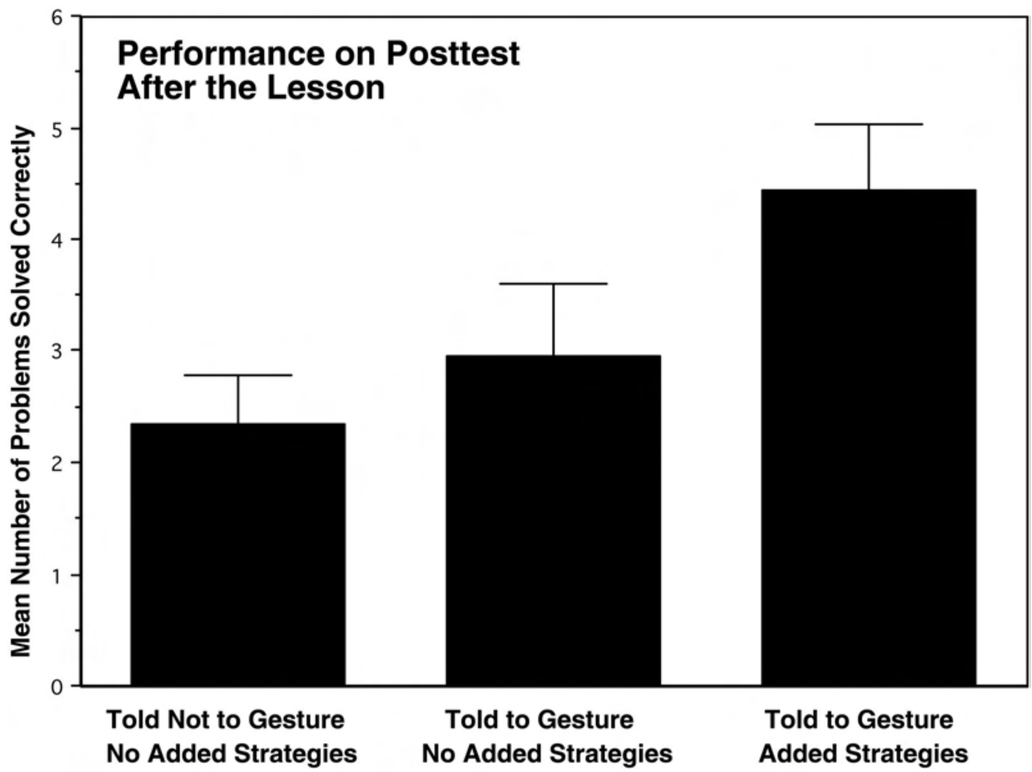

Figure 4. Mean number of problems solved correctly on the posttest by children categorized according to condition and whether they added strategies during the manipulation phase of Study 2. Children who were told to gesture were divided into those who added strategies during the manipulation and those who did not add strategies. None of the children who were told not to gesture added strategies during the manipulation (see Figure 3, top panel). Error bars represent standard errors.

gesture manipulation and posttest performance nonsignificant, and it did. The F value dropped from 4.41 to less than 1.00.

Another way of looking at this same question is to divide the told-to-gesture group into children who added strategies as a result of being told to gesture ($N = 16$) and children who did not add strategies when told to gesture ($N = 20$) and to then compare their posttest performance with that of the children in the told-not-to-gesture group ($N = 34$), none of whom added strategies during the manipulation. We found significant differences in posttest performance across these three groups, $F(2, 67) = 3.66$, $p = .03$, $\eta_p^2 = .052$. Children who added strategies when told to gesture solved significantly more problems correctly on the posttest than did children told not to gesture (see Figure 4; $p < .03$, Newman–Keuls). In contrast, children who did not add strategies when told to gesture did not solve significantly more problems correctly than did children told not to gesture (see Figure 4; $p = .40$, Newman–Keuls).[1] Thus, it was not merely being told to gesture but expressing implicit problem knowledge via gesture that led to better posttest performance.

Even children who produced no gestures at baseline improved on the posttest if they added strategies during manipulation, although the numbers were too small to test for statistical significance. Of the 8 children who produced no gestures at baseline and were told to gesture, the 3 who added strategies solved a mean of 3.7 ($SD = 3.2$) problems correctly on the posttest; the 5 who did not add strategies solved only an average of 1.2 ($SD = 2.8$). In comparison, the 12 children who produced no gestures at baseline and were told not to gesture (and added no new strategies) solved a mean of 1.9 ($SD = 2.2$) problems correctly. Thus, our manipulation did not merely stimulate a tendency to gesture that children brought with them to the task. For some, it instilled a new behavior.

Telling children to gesture was enough to get them to produce new strategies, and producing those new strategies appeared to prepare them for learning. Note that the new strategies did not come about just because the children were asked to focus attention during their explanations: Children in both conditions were instructed to allocate attention to their hands when they explained the problems (either to move them or to keep them still). But only the children told to move their hands (i.e., gesture) added new strategies to their repertoires and, in turn, profited from the math lesson.

[1] It is possible that being told not to gesture interfered with children's ability to profit from instruction. However, the fact that children who were told not to gesture solved the same number of posttest problems ($M = 2.3$, $SD = 2.6$) as did children who were told to gesture but did not add strategies to their repertoires ($M = 2.9$, $SD = 2.9$) makes this hypothesis unlikely.

Discussion

Previous studies have shown that having implicit knowledge predicts subsequent behavior. But to our knowledge, ours is the first study to demonstrate that the expression of new implicit knowledge can be externally manipulated (in this case, by instructions to gesture) and that this expression of implicit knowledge can pave the way for learning. We conducted two studies exploring the role that implicit knowledge plays in learning. In the first, we stimulated a vehicle through which implicit knowledge is often expressed (the gestural modality) and found that the manipulation increased the expression of implicit knowledge. The manipulation did not just reveal a vague feeling of knowing or an ability to choose the correct answer at above-chance levels: It revealed substantive and previously unseen problem-specific knowledge. In the second study, we found that stimulating the expression of implicit knowledge not only revealed new implicit knowledge, it also increased receptivity to instruction. Children told to gesture were more likely to learn from instruction than were children told not to gesture. It is important to note that the effect that being told to gesture had on learning disappeared when strategies added while gesturing was included in the analysis as a covariate. This finding suggests that changes in implicit knowledge underlie the learning effect.

Forced Gesture Still Taps Implicit Knowledge

Speakers often express information in their spontaneous gestures that is not found anywhere in their speech (Goldin-Meadow, 2003). But will speakers continue to express implicit knowledge in gesture if they are told to move their hands? We found that children told to gesture when explaining their solutions to a series of math problems added new strategies, produced uniquely in gesture, to their repertoires. The implicit strategies the children produced in gesture were not only new to their repertoires, the strategies were mostly correct. According to any traditional measure, the children in our study did not understand the math problems we gave them: They always gave wrong answers to the problems and always gave incorrect problem-solving strategies in speech to explain those answers. Nevertheless, when told to gesture, the children produced correct problem-solving strategies in gesture (while continuing to solve the problems incorrectly in speech).

A priori we might have guessed that speakers forced to move their hands when talking would focus on their gestures and attempt to convey the same (in this case, incorrect) information in gesture as they convey in speech (see Perner & Dienes, 1999, p. 799; Goldin-Meadow & Alibali, 1999). But this guess turns out to be wrong: Forcing speakers to gesture seems to encourage them to produce information in gesture that is not found in their speech. Speakers who consciously gesture do not seem to be any more in control of the content of their gestures than are speakers who gesture spontaneously. Gesturing seems to be like walking, or perhaps like driving a stick-shift car for an expert: It is a skill that can be consciously activated but, once activated, seems to run automatically with little conscious reflection. Indeed, there is likely to be a decrease in proficiency when one consciously attends to performing a skill of this type (Beilock, Carr, MacMahon, & Starkes, 2002). The difference between driving a stick-shift car and gesturing is that one does not have to be explicitly taught to gesture. Indeed, one does not have to ever have seen a person gesture to gesture while talking: Individuals who have been blind from birth gesture when they speak, even when addressing other blind individuals (Iverson & Goldin-Meadow, 1998). All one needs to begin gesturing while speaking is to learn to talk. Gesture's automaticity may therefore be difficult to disrupt.

Why Does Making Children Gesture Bring Out Their Implicit Knowledge?

We show here that forcing children to move their hands when explaining how they solved math problems can lead them to express entirely new—and correct—problem-solving strategies that they did not display before. Why? Perhaps forcing children to move their hands as they talk encourages them to notice previously unseen aspects of a problem. Indeed, forcing children to gesture while being interviewed about an event encourages them to recall information that can easily be captured in gesture (e.g., size, shape, location; Stevanoni & Salmon, 2005). Moving their hands may have encouraged the children who participated in our study to notice those aspects of the math problems that lend themselves to gestural representation. For example, a child might be drawn to the two numbers in the problem that are identical and, if encouraged to gesture, might point first at these two numbers and then at the remaining two numbers in the problem. These movements instantiate the equal-addends and grouping strategies frequently produced by children who do know how to solve the math problems (see Table 1). Note that producing a correct strategy in gesture did not mean that the child solved the problems correctly. In fact, the children who expressed correct problem-solving strategies uniquely in gesture were, at that moment, not solving the problems correctly. But producing a correct strategy in gesture did seem to make the children more receptive to the later math lesson.

In this regard, it is important to note that if left to their own devices, the children would have become more and more entrenched in their incorrect answers (cf. Goldin-Meadow & Alibali, 2002). The math problems we used in our study are typically not solved by third and early fourth grade children without instruction, unlike the kinds of problems typically used in studies of implicit knowledge, which can be solved by participants on their own. It is therefore quite surprising that merely asking children to move their hands during the math explanations revealed correct problem-solving strategies. This is an important finding, not only in terms of shedding light on the relation between gesture and learning but also in terms of understanding how explicit instructions can elicit implicit knowledge.

Noticing aspects of the world that are easily encoded in gesture seemed to help children learn how to solve the math problems in our study. However, just as encoding information in speech does not always lead to efficient processing (Berry & Broadbent, 1984; Schooler et al., 1993), encoding information in gesture can sometimes lead to inefficient strategies. Take, for example, a gear task originally studied by Schwartz and Black (1996). The adult is asked to imagine an array of gears described by the experimenter and to predict how a target gear will move when one of the other gears is moved. In Schwartz and Black's study, adults who were allowed to gesture while solving the problems used a strategy in which they modeled the movement of each individual gear (usually in gesture). In contrast, adults who were prevented from gesturing generated rule-based strategies (e.g., if there are an odd number of gears, the last gear goes in the same direction as the first). Rule-based strategies are a more efficient way of solving the gear task, and adults who gestured when doing the task were less likely than adults who did not gesture to arrive at these efficient strategies (Alibali, Spencer, & Kita, 2004, as described in Alibali, 2005). Thus, just as verbalizing hard-to-verbalize tasks tends to be disruptive and verbalizing easily verbalized tasks tends to be helpful (Schooler, Fiore, & Brandimonte, 1997), gesturing on tasks whose solutions do not lend themselves to gesture seems to be disruptive and (as we find here) gesturing on tasks whose solutions can, at least initially, be more easily grasped in gesture tends to be helpful.

Bringing Out Implicit Knowledge Through Gesture Prepares Children for Learning

Implicit knowledge has often been found to precede explicit knowledge. For example, Siegler and Stern (1998) observed second-grade children learning a short-cut strategy for solving a simple addition problem (e.g., $28 + 36 - 36 =$ __, where the two 36s can be canceled, leaving 28 as the answer). By examining solution times, Siegler and Stern found that almost all of the children displayed an implicit understanding of the short-cut strategy several trials before they were able to articulate it in speech. Findings of this sort suggest that an implicit understanding precedes learning, but such findings do not demonstrate that implicit knowledge plays a causal role in learning. Indeed, the case cannot be made unless implicit knowledge is experimentally manipulated. We did just this in the current work.

The unique contribution of this study is that we manipulated a vehicle through which implicit knowledge is often expressed (gesture) and observed the effect of that manipulation on learning. We found that children who were told to gesture when explaining a math task produced previously unexpressed, implicit knowledge on the task and were later receptive to instruction on the task. Even children who produced no gestures at all at the beginning of the study were likely to learn the task if they displayed implicit knowledge when told to gesture. The act of gesturing can thus bring out implicit knowledge, which, in turn, makes learners receptive to instruction. In this way, gesturing can play a causal role in learning.

It is important to note that the children in our study were not actively gesturing during the math lesson—all of their gesturing was done before the lesson began. Thus, moving the body does not have to be done at the time of learning to have an impact on learning.

Did our manipulation create new knowledge in the children who were told to gesture? We cannot be sure. All of the children who were told to gesture moved their hands, but only some added new and correct strategies to their repertoires. These children may have had these correct strategies in their repertoires before receiving our instructions to gesture. But, if so, it is likely that at least some children in the told-not-to-gesture group also had correct strategies in their repertoires at the start of the study (albeit not expressed, not even in gesture). If these children did have correct knowledge before our study began, not being able to gesture appeared to prevent them from capitalizing on it. Although we cannot be certain from this study that being told to gesture creates new implicit knowledge (but see Cook, Mitchell, & Goldin-Meadow, in press), we do know that being told to gesture can, at the least, reveal previously unexpressed implicit knowledge that, in turn, makes learning more likely.

Why does implicit knowledge play a role in learning? Sun, Merrill, and Peterson (2001) hypothesized that there is a synergy between explicit and implicit performances. This synergy has the potential to speed up learning, improve learned performance, and facilitate the transfer of learned skills. Sun and colleagues found that performance in their skill-learning model decreased when either the level corresponding to explicit knowledge or the level corresponding to implicit knowledge was removed from the model (Sun & Peterson, 1998), thus demonstrating the need for both levels. In this regard, it is significant that the children who expressed correct implicit knowledge when told to gesture still did not solve the problems correctly during the manipulation. They had to wait until they received explicit instruction on the problems to reap the full benefits of their implicit knowledge. Conversely, one reason self-explanations (the explicit explanations students spontaneously produce in talk-aloud protocols when studying problems) work to promote learning (Chi, Bassok, Lewis, Reimann, & Glaser, 1989) may be because the learner, in addition to generating explicit statements about the problems, could also be gesturing and thus revealing (and perhaps creating) implicit knowledge at the same time. Having both forms of knowledge may be the best recipe for promoting change.

Implications

We have shown that by encouraging children to gesture, we could get them to reveal new and correct problem-solving strategies not previously found in either their gestures or their speech. These new strategies were, for the most part, revealed exclusively in the children's gestures and, in this sense, reflected implicit knowledge. Moreover, adding new strategies to their repertoires as a result of being told to gesture when solving problems before a lesson made children particularly receptive to the lesson.

Studies often distinguish two levels of knowing (explicit vs. implicit; conscious vs. unconscious; controlled vs. automatic). However, knowledge can be represented at many levels (Karmiloff-Smith, 1986, 1992). We suggest that the gestures speakers produce when they talk provide insight into a level of representation that is neither fully explicit nor fully implicit. Gestures that express information not found in speech seem to represent an intermediate point along a continuum of knowledge ranging from fully implicit and embedded in problem-solving procedures to fully explicit and accessible to verbal report (Goldin-Meadow & Alibali, 1994). Information found only in gesture and never verbalized is, by definition, not explicit. But knowledge expressed uniquely in gesture is not fully implicit either: It is, after all, visible on the hands. Speakers have limited access to such knowledge; they can, for example, make judgments on the basis of knowledge they express solely in gesture (Garber et al., 1998). Moreover, as our findings suggest, telling speakers to gesture brings out, in gesture, knowledge that speakers do not yet verbalize, which can, in turn, support learning explicit strategies. Gesture thus has the potential to be an important way station in the progression from implicit to explicit knowledge—one that offers unique insight into implicit thought and, as we have shown here, one that can be manipulated to good effect.

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