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The Role of Gesture in Learning: Do Children Use Their Hands to Change Their Minds?

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Adding gesture to spoken instructions makes those instructions more effective. The question we ask here is why. A group of 49 third and fourth grade children were given instruction in mathematical equivalence with gesture or without it. Children given instruction that included a correct problem-solving strategy in gesture were significantly more likely to produce that strategy in their own gestures during the same instruction period than children not exposed to the strategy in gesture. Those children were then significantly more likely to succeed on a posttest than children who did not produce the strategy in gesture. Gesture during instruction encourages children to produce gestures of their own, which, in turn, leads to learning. Children may be able to use their hands to change their minds.

Gesture is often used in teaching contexts (Flevares & Perry, 2001; Goldin-Meadow, Kim, & Singer, 1999; Neill, 1991) and, when used in these contexts, gesture promotes learning. Children are more likely to profit from instruction when the instruction includes gesture than when it does not (Church, Ayman-Nolley, & Estrade, 2004; Perry, Berch, & Singleton, 1995; Singer & Goldin-Meadow, 2005; Valenzeno, Alibali, & Klatzky, 2003). Why might gesture in instruction lead to learning?

The gestures teachers produce during instruction could facilitate learning by helping children understand the words that accompany those gestures. Presenting information in more than one modality is generally associated with learning (Mayer & Moreno, 1998) and listeners are often better able to grasp the message conveyed in a speaker's words when that message is also conveyed in gesture than when it is conveyed only in speech (Goldin-Meadow et al., 1999; Goldin-Meadow

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& Singer, 2003; Kelly, Barr, Church, & Lynch, 1999; Thompson & Massaro, 1986, 1994).

But the gestures teachers produce during instruction could also have an impact on learning by encouraging children to produce gestures of their own. Adults have been shown to mimic nonverbal behaviors that their conversational partners produce (e.g., their partner's facial expressions or idiosyncratic motor behaviors, Chartrand & Bargh, 1999) and even very young infants can imitate nonverbal behaviors modeled by an experimenter (Meltzoff & Moore, 1977). It would therefore not be at all surprising if we were to find that school-aged children imitate the gestures that their teachers produce. The question, however, is whether children can learn how to solve a problem from imitating their teacher's gestures.

Teachers routinely produce gestures when they explain math problems to their students (Flevares & Perry, 2001). For example, when instructing children in mathematical equivalence problems (e.g., $7 + 6 + 3 = \_\_ + 3$), teachers produce gestures that convey strategies for solving those problems (e.g., they point at the 7 and the 6 and then the blank to indicate that these two numbers can be grouped and added to generate the number that goes in the blank—a "grouping" problem-solving strategy; Goldin-Meadow et al., 1999). Children spontaneously produce these same problem-solving strategies in their own gestures and, when they do, they seem to have implicit understanding of how those strategies work. For example, children who produce the grouping strategy in gesture can recognize a correct solution to the math problem even though they do not produce grouping (or any other correct strategy) in their speech and cannot solve the problem on their own (Garber, Alibali, & Goldin-Meadow, 1998). But what happens when children who do not spontaneously produce correct strategies in gesture imitate gestures conveying a correct problem-solving strategy?

In an imitation task, children typically learn to reproduce behaviors performed by a model. Young children are able to imitate behaviors that have no apparent goal (e.g., protruding the tongue; Meltzoff & Moore, 1977), but they are also able to imitate behaviors that are goal directed (e.g., touching the forehead to a panel that turns on a light; Meltzoff, 1988; see also Bekkering, Wohlschlaeger, & Gattis, 2000; Carpenter, Call, & Tomasello, 2005). Moreover, when children imitate goal-directed behaviors, they seem to understand the goals motivating those behaviors. For example, when shown a model who touches her forehead to a panel to turn on a light, children seem to know that the model's goal is to turn on the light. Indeed, they can invent new ways of reaching the goal if the model's method for turning on the light seems not to be essential to that goal (e.g., if the model's hands are full when she touches her forehead to the panel, children assume that circumstance is forcing the model to use her head rather than her hands to turn on the light, and they themselves use their hands to turn on the light; Gergely, Bekkering, & Király, 2002). Note, however, that in the light-turning-on task, a child *could* bring about the goal even if that child did not understand the causal relation between contacting the panel and turning on the light—all the child needs to do is uncomprehendingly imitate the model's actions and the light will go on.

But imitating gesture is different. A math teacher's gestures represent a series of steps that, if taken, lead to a correct solution to the problem. However, the gestures are not themselves the steps. Mindlessly copying a teacher's points at the 7 and the 6 will not, in and of itself, produce the correct answer to the 7 + 6 + 3 = __ + 3 problem. To figure out how to solve the problem, children must not only reproduce the teacher's gestures, they must also understand what those gestures represent. If children understand the meanings conveyed by the gestures they repeat, producing those gestures might be able to lead to learning.

Producing gesture has been found to be associated with learning in nonimitative contexts. For example, children who are at a transitional point in acquiring a task produce gestures that differ from the gestures they produce when not at a transitional point; in particular, their gestures convey information not found anywhere in their speech (Church & Goldin-Meadow, 1986; Goldin-Meadow, Alibali, & Church, 1993; Perry, Church, & Goldin-Meadow, 1988; Pine, Lufkin, & Messer, 2004). As another example, children produce more substantive gestures when they are asked to reason about objects than when asked to merely describe those objects (i.e., when they are asked to think deeply about a task; Alibali, Kita, & Young, 2000). Finally, children who express their budding knowledge in gesture as they learn a task are more likely to retain their new knowledge than children who do not use gesture in this way (Alibali & Goldin-Meadow, 1993).

The gestures children produce on a task have thus been shown to *reflect* their knowledge of the task, particularly at moments of transition. In previous studies, children were not encouraged to gesture but produced their gestures spontaneously. As a result, their gestures could have been an epiphenomenon of their readiness-to-learn—that is, the gestures could have reflected the state of the children's knowledge but played no role in changing that knowledge. Our hypothesis in this study, however, is that gesturing goes beyond reflecting knowledge and plays a role in *creating* new knowledge. To determine whether the act of gesturing itself plays a role in learning, we need to experimentally manipulate gesturing—to increase the rate at which children gesture and observe the effects of that increase on learning.

Our first goal, then, is to increase the rate at which children gesture by exposing them to gesture. We ask whether having teachers gesture while instructing children increases the likelihood that children will produce gestures of their own during that instruction. We expect that it will. If it does, we can then pursue our second goal—to examine the relation between children's production of gesture and learning. We ask whether children who produce gestures of their own during instruction learn the task more readily than children who do not produce gestures.

METHOD

Participants

A total of 49 (30 girls, 19 boys) late third grade and early fourth grade children (9–10 years old) participated in the study. An additional 19 children took the pretest but were successful on some of the pretest problems and were eliminated from the study. Children were recruited through public and private elementary schools in the Chicago area. They came from lower and middle class neighborhoods and from a variety of racial and ethnic backgrounds (White 27%, African American 37%, Hispanic 29%, Asian or Pacific Islander 8%).

Procedure

Pretest. Children were asked to solve a pencil-and-paper pretest consisting of six mathematical equivalence problems with equivalent addends (4 + 6 + 3 = 4 + __) and six mathematical equivalence problems without equivalent addends (7 + 3 + 4 = 5 + __). None of the children solved any of the pretest problems correctly. After children completed the pretest, they explained their solutions to the six problems with equivalent addends to an experimenter at a whiteboard.

Instruction. A second experimenter, the instructor, then taught each child individually at the whiteboard. The instructor showed the child how to solve six mathematical equivalence problems with equivalent addends. After each problem, the child was given a problem of the same type of his or her own to solve and explain. The children thus solved six problems on their own during the instruction period. The instructor presented the equalizer strategy on all of the problems she taught—the notion that the two sides of an equation need to be considered separately and must be equal to one another. For example, on the problem 4 + 6 + 3 = __ + 3, the teacher put 10 in the blank and said, "I wanted to make one side equal to the other side. See 4 plus 6 plus 3 equals 13, and 10 plus 3 equals 13. That's why I put 10 in the blank. So one side is equal to the other side." Children produced a variety of correct and incorrect solutions and explanations during instruction, which were later tabulated and analyzed.

Instruction varied along two dimensions. First, we manipulated whether the instructor's explanations contained gesture. In the Speech alone condition, the instructor clasped her hands at her waist while giving the equalizer explanation in speech. In the Speech + Gesture condition, the instructor swept her left hand under the left side of the equation each time she said "one side," and then swept her right hand under the right side of the equation when she said "the other side." No other gestures were produced by the instructor during training. Second, we manipulated the children's attention to gesture and also their attention to speech. In the

Copy-Gesture condition, children were encouraged to copy the instructor's gestures when they produced their own explanations: "During your explanation, try to move your hands the way I did." In the Copy-Speech condition, children were encouraged to copy the instructor's words: "During your explanation, try to say something like what I said." Two control groups of children were given instruction in mathematical equivalence, one group with gesture and one without gesture, but were not encouraged to copy the instructor's speech or gesture.

This design resulted in five instructional conditions: (a) Speech alone, no copying instructions ($n = 10$); (b) Speech alone, child instructed to copy speech ($n = 10$); (c) Speech + Gesture, no copying instructions ($n = 10$); (d) Speech + Gesture, child instructed to copy speech ($n = 10$); and (e) Speech + Gesture, child instructed to copy gesture ($n = 9$). Children were randomly assigned to one of the five conditions prior to taking the pretest.

Children in the three copy conditions were reminded of the instructions to copy on each problem; children in the two control groups were reminded to explain their answers carefully on each problem. With the exception of the verbal instructions to copy, the experimenter followed identical verbal scripts across all five conditions. Children who asked questions during training were not given additional instruction beyond the script; they were simply instructed to "just solve the problem however you think best." Spot checks of a random sample of the video clips revealed that the instructors were nearly perfect in following the experimental script; of 49 instructional trials checked, only 1 contained a minor deviation from the script.

Posttest. Immediately after the instruction period, children completed a posttest, which was identical in form to the pretest and was administered by the first experimenter.

Coding the Children's Gestures

The speech and gesture that the children produced during the entire session were transcribed and coded for problem-solving strategies according to a previously developed system (Perry et al., 1988). Speech and gesture were coded separately; speech was coded with the picture turned off, and gesture was coded with the sound turned off. A second trained coder independently transcribed a subset of the data to establish reliability. Agreement between coders was .93 ($N = 56$) for assigning strategies to speech and .84 ($N = 50$) for assigning strategies to gesture.

We tabulated the number of times each child produced an equalizer strategy (the strategy taught by the instructor) in speech or in gesture during the instruction period. The children received credit for having produced an equalizer strategy even if they did not copy the instructor's speech or gesture exactly; 86% of the children's equalizer strategies in gesture were nearly identical to the instructor's, as were 46% of their equalizer strategies in speech. When children varied from the instructor's spoken model, they tended to state the equivalence of the two sides of the equation rather than go through the addition steps. For example, for the problem 4 + 6 + 3 = __ + 3 a child might say, "This side is 13 and the other side is 13." When children varied from the instructor's gesture model, they tended to substitute points for the sweeping hands. For example, a child might point at each number on the left side with the left hand, and then point at each number on the right side with the right hand (rather than sweeping the left hand under the left side and the right hand under the right side of the equation). The pattern of results reported later remains the same even if we restrict the data to exact copies.

RESULTS

Does Gesture in Instruction Encourage Children to Produce Gestures of Their Own?

We begin by examining the effect of the instructor's gestures on children's gestures during instruction. In an analysis of covariance with number of times that children gestured on the pretest as a covariate, modality of the instructor's explanations (Speech only, Speech + Gesture) as a factor, and number of times that children gestured during training as the dependent measure, we found a significant interaction between instructor input and the number of times that children gestured during the pretest. Children who did not gesture very much on the pretest (gesture on 0–3 pretest problems, $N = 24$) significantly increased their gesture during training if they were in the Speech + Gesture condition but not if they were in the Speech only condition, estimated means: No gesture on pretest, 0.6 (Speech only) versus 4.0 (Speech + Gesture), $p = .001$; gesture on 1 pretest problem, 1.3 versus 4.1, $p = .001$; gesture on 2 pretest problems, 0.1 versus 4.3, $p = .002$; gesture on 3 pretest problems, 2.8 versus 4.4, $p = .009$. In contrast, children who gestured on most of the pretest problems (gesture on 4–6 pretest problems, $N = 25$) continued to gesture during training regardless of instructor input. There were no significant differences in the number of problems with gesture during training for these children. Thus, children who saw gesture also gestured during training regardless of their gesturing on the pretest, whereas children who did not see gesture only gestured during training if they had gestured on most of the pretest problems. Importantly, the number of children who produced gesture on 0–3 versus 4–6 pretest problems did not differ between the Speech + Gesture and the Speech only instruction conditions.

Were the children's gestures imitations of the instructor's gesture? We next calculated the number of times each child produced the same strategy as the instructor (equalizer) in gesture during instruction. In an analysis of variance (ANOVA) with the modality of the instructor's explanations (Speech only, Speech + Gesture) as a

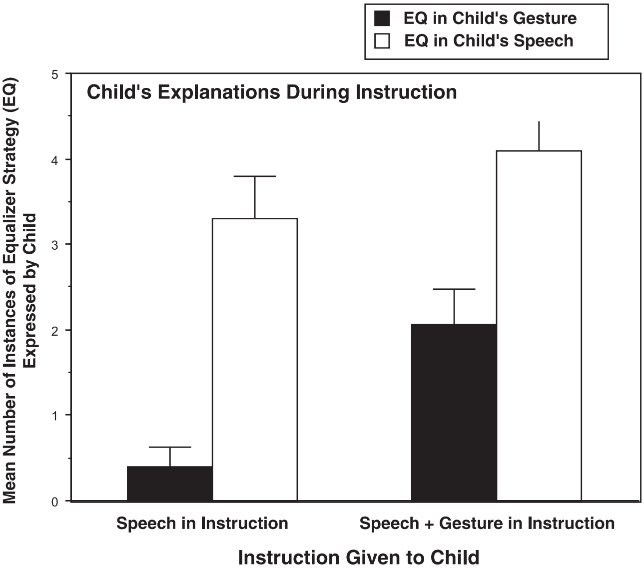

FIGURE 1 Mean number of equalizer strategy explanations children produced when given instruction with gesture and without it. Children given instruction in speech and gesture expressed significantly more equalizer strategies in gesture than children given instruction in speech alone. There were no significant differences between the groups in number of equalizer strategies expressed in speech. Error bars represent standard errors.

factor and the number of times children gestured the equalizer strategy during instruction as the dependent measure, we found a significant effect of instructor's gesture on the form of children's gesture. Children in the Speech + Gesture condition produced the equalizer strategy in gesture on significantly more problems during the instruction period than children in the Speech alone condition, 2.1 versus 0.4, $F(1, 47) = 10.28$, $p = .002$; see Figure 1. None of the children in either group produced the equalizer strategy in gesture (or in speech, for that matter) on the pretest. Thus, children who saw the instructor gesture were not merely waving their hands in response. Rather, these children were picking up on, and reproducing, the content of the instructor's gesture. Furthermore, this effect did not interact with children's pretest gesture production. Children who did not gesture very much on the pretest (gesture on 0–3 pretest problems) were as likely to gesture the instructor's strategy (42% gestured equalizer during training) as children who gestured a lot on the pretest (gesture on 4–6 pretest problems, 48% gestured equalizer during training). Thus, children's likelihood of picking up on the instructor's gesture was not related to their own propensity to produce gesture.

In contrast to these gesture findings, there was no effect of our manipulations on speech. In an ANOVA with the modality of the instructor's explanations (Speech only, Speech + Gesture) as a factor and the number of times children *said* the equalizer strategy during instruction as the dependent measure, we found no effect of instructor's gesture on children's speech. Children in both groups produced the equalizer strategy in speech on approximately the same number of problems during the instruction period, 4.1 versus 3.3, *F*(1, 47) = 1.90, *ns;* see Figure 1. Including gesture along with speech in the instructions had no impact on how often the children repeated the instructor's speech.

In sum, our attempts to manipulate children's gesture by *modeling* gesture had the desired effect—children who saw gesture produced gesture, and their gestures reflected the content of the gestures that they saw. Furthermore, this effect did not appear to be mediated by children's understanding of the instructor's speech, or by children's own propensity to gesture.

In contrast, our efforts to manipulate children's gesture by *asking* them to copy the instructor's gesture were not successful. The number of times the children in the Speech + Gesture condition expressed the equalizer strategy in gesture did not differ significantly across the three groups who saw gesture, Speech + Gesture, No instructions to copy 1.5; Speech + Gesture, Instructions to copy speech 1.7; Speech + Gesture, Instructions to copy gesture 3.1; *F*(2, 26) = 1.59, *ns*. Our efforts to manipulate children's speech by asking them to copy the instructor's speech were also not successful (although this noneffect could reflect the fact that almost all of the children produced the equalizer strategy in speech during the instruction period; i.e., there may have been a ceiling effect). In an ANOVA with experimental condition as a factor and the number of times the children expressed the equalizer strategy in speech as the dependent measure, we found no differences across the five experimental conditions: Speech, No instructions to copy 2.7; Speech, Instructions to copy speech 3.9; Speech + Gesture, No instructions to copy 3.5; Speech + Gesture, Instructions to copy speech 4.2; Speech + Gesture, Instructions to copy gesture 4.7; *F*(1, 44) = 1.34, *ns.*

To summarize thus far, adding gesture to instruction affected children's behavior in a predictable way. Children who saw gesture gestured more, and they were more likely to gesture the particular strategy, equalizer, that they saw in gesture. Furthermore, adding gesture to the lesson increased the children's production of the equalizer strategy in gesture without affecting their production of the equalizer strategy in speech.

Are Children Who Gesture During Instruction More Successful on the Math Problems They Solve During That Instruction Period Than Children Who Do Not Gesture?

The children imitated the gestures that the instructor produced. But did they understand the gestures they imitated? If the children understood the meaning of the gestures they copied, they might be able to use the strategy conveyed by those gestures to good effect. In particular, children who produced the equalizer strategy in gesture might do better on the math problems they solved than children who did not produce the strategy in gesture. We explored this prediction first for the six problems that children solved on their own during the instruction period.

Did children who gestured the equalizer strategy during instruction solve more problems correctly during that same instruction period than children who did not gesture the equalizer strategy? Collapsing the data across the five conditions, we divided children into three groups: (a) 22 children who expressed the equalizer strategy in *gesture* during the instruction period (all of these children also expressed the equalizer strategy in speech), (b) 21 children who expressed the equalizer strategy in *speech* but not in gesture during the instruction period, (c) and 6 children who did not express the equalizer strategy in either gesture or speech during the instruction period.

We calculated the total number of problems (out of six) during the instruction period that the children in each group solved correctly (see Figure 2). In an ANOVA with children's explanations during instruction (Never expressed the equalizer strategy, Expressed the equalizer strategy in speech only, Expressed the equalizer strategy in speech and gesture) as a factor, and the number of problems solved correctly during instruction as the dependent measure, we found that chil-

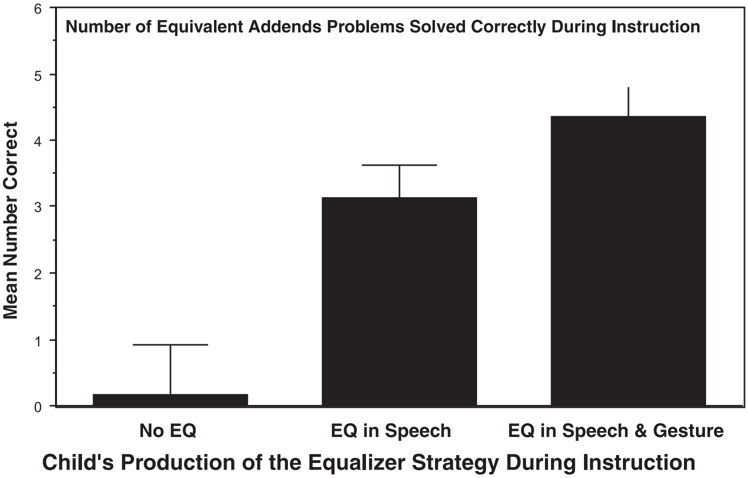

FIGURE 2 Mean number of equivalent addends problems (out of 6) solved correctly during instruction. Children are categorized according to the modality in which they produced the equalizer strategy during the instruction period. Children who produced the equalizer strategy in speech, with or without gesture, solved significantly more problems correctly during instruction than children who did not produce the equalizer strategy at all. Error bars represent standard errors.

dren's problem-solving success during instruction was significantly related to their speech and gesture performance during instruction, $F(2, 46) = 12.88, p < .001$. Not surprisingly, children who expressed the equalizer strategy in both speech and gesture during instruction solved significantly more problems correctly than children who never expressed the equalizer strategy (4.36 vs. 0.17, $p < .001$, Tukey–Kramer), as did children who expressed the equalizer strategy in speech alone (3.14 vs. 0.17, $p < .01$, Tukey–Kramer). However, children who expressed the equalizer strategy in speech and gesture solved only marginally more problems correctly during instruction than children who expressed the equalizer strategy in speech only (4.36 vs. 3.14, $p = .08$, Tukey–Kramer). Thus, gesturing the equalizer strategy during instruction was not reliably associated with success in solving the math problems during instruction. Children who said the equalizer strategy (and did not gesture it) during instruction solved nearly as many problems correctly during instruction as children who both said and gestured the equalizer strategy.

Importantly, we see this same pattern no matter what type of instruction the children received. Table 1 presents the mean number of problems (out of six) solved correctly by children in each of the five conditions in the study; children are categorized according to the modality in which they expressed the equalizer strategy during the instruction period. Note that, in each of the five conditions, children who did not produce the equalizer strategy solved fewer problems correctly during instruction than children who produced the equalizer strategy in speech only or in both speech and gesture.[1]

Are Children Who Gesture During Instruction More Likely to Retain and Generalize the Knowledge They Gain Than Children Who Do Not Gesture?

Children who produced the equalizer strategy in gesture during instruction performed slightly (but not significantly) better on the math problems they solved during the instruction period than children who did not produce the strategy in gesture. Articulating a problem-solving strategy in gesture thus had no reliable effect on how the problem was actually solved, above and beyond the effect of articulating the problem-solving strategy in speech. We therefore do not yet have convincing evidence that the children understood and profited from the equalizer gestures they produced.

But gesturing a problem-solving strategy might have an impact on whether the strategy is retained and generalized to other problems (see, e.g., Alibali &

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[1] These effects, as well as the effects observed on posttest performance, were not modulated by children's propensity to produce gesture on the pretest. There were no significant interactions of children's gesture on the pretest, children's gesture during training, and children's problem-solving success during training or on the posttest problems.

TABLE 1

Mean Number of Math Problems Solved Correctly During Instruction as a Function of Experimental Condition and Child's Production of the EQ Strategy During Instruction and Number of Children Who Contributed to Each Mean

	Experimenter Modeled EQ Strategy in Speech				*Experimenter Modeled EQ Strategy in Speech and Gesture*					
	No Instructions to Copy		*Instructions to Copy*		*No Instructions to Copy*		*Instructions to Copy Speech*		*Instructions to Copy Gesture*	
Children Classified According to Their Production of the EQ Strategy During Instruction	*M*	*n*	*M*	*n*	*M*	*n*	*M*	*n*	*M*	*n*
Never expressed EQ	0.33	3	0.00	1	0.00	1	—	0	0.00	1
Expressed EQ in speech only	2.80	5	2.43	7	4.33	3	3.00	4	5.00	2
Expressed EQ in speech and gesture	5.00	2	5.50	2	4.00	6	4.00	6	4.36	6
Total	2.50	10	2.80	10	3.70	10	3.60	10	4.11	9

Note. EQ = Equilizer. The mean number of correct answers given during training (out of 6 equivalent addends problems total). Children are classified according to the modality in which they expressed the EQ strategy during the instruction period.

Goldin-Meadow, 1993). To explore this possibility, we examined how well children performed on the posttest. The posttest contained two types of problems: six problems with equivalent addends comparable to the problems used during instruction (e.g., $4 + 6 + 3 = 4 + \_\_$) and six problems with nonequivalent addends (e.g., $7 + 3 + 4 = 5 + \_\_$) requiring transfer of the knowledge learned to a new type of problem.

Data were entered into ANOVAs with children's explanations during instruction (Never expressed the equalizer strategy, Expressed the equalizer strategy in speech only, Expressed the equalizer strategy in speech and gesture) as a factor and posttest performance (Number of equivalent addends problems solved correctly and Number of nonequivalent addends problems solved correctly) as the dependent measures. The children's performance on the posttest problems with equivalent addends was significantly related to their explanations during instruction, $F(2, 46) = 11.12$, $p < .001$ (see Figure 3, top graph). Children who expressed the equalizer strategy in speech and gesture solved significantly more equivalent addends problems correctly than children who did not express the equalizer strategy in either speech or gesture during instruction (4.5 vs. 0.0, $p < .001$, Tukey–Kramer). Moreover, the children who expressed the equalizer strategy in speech and gesture also solved significantly more problems than children who expressed the equalizer strategy in speech alone (4.5 vs. 2.5, $p < .001$), who, in turn, solved significantly more equivalent addends problems than children who did not express the equalizer strategy at all (2.5 vs. 0.0, $p = .039$).[2] Thus, expressing information in gesture as well as speech helped children retain knowledge gained during instruction better than expressing information in speech alone.

The children's performance on the transfer posttest problems with nonequivalent addends was also significantly related to their explanations during instruction, $F(2, 46) = 7.4$, $p = .002$, and revealed a similar pattern (see Figure 3, bottom graph). Children who expressed the equalizer strategy in speech and gesture solved significantly more transfer problems correctly than children who did not express the equalizer strategy in either speech or gesture during instruction (4.1 vs. 0.0, $p < .001$). The children who expressed the equalizer strategy in speech and gesture also solved more transfer problems than children who expressed the equalizer strategy in speech alone (4.1 vs. 2.6, $p < .096$), who, in turn, solved more problems than children who never expressed the equalizer strategy (2.6 vs. 0.0, $p < .063$), although these differences did not reach statistical significance. Thus, expressing information in gesture as well as speech helped children extend knowledge gained during instruction better than expressing information in speech alone.

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[2] Most of the correct explanations that the children produced on the posttest were equalizer explanations (90%, 143/159; children gave explanations only on the six problems on the posttest that contained equivalent addends). This finding reinforces the fact that the children really were influenced by the instruction given to them.

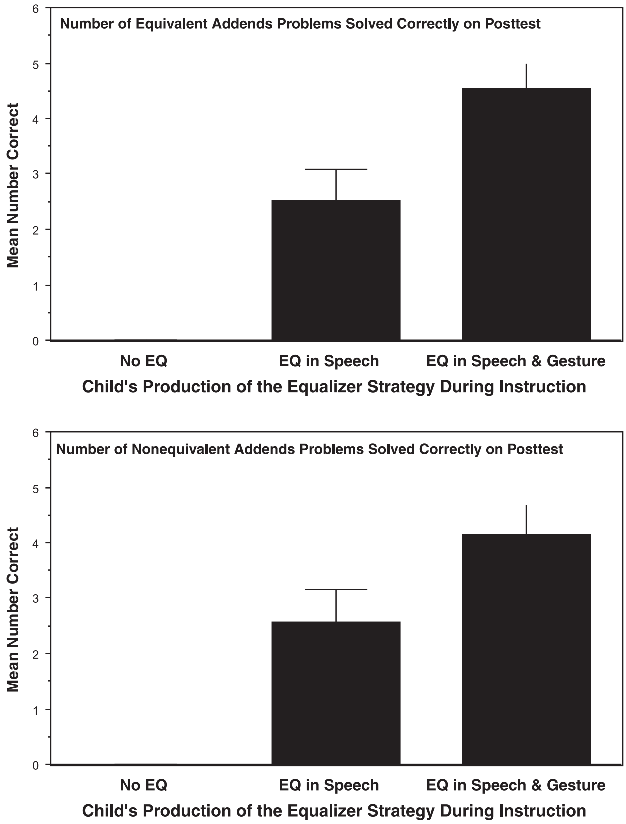

FIGURE 3 Mean number of equivalent addends problems (top graph) and nonequivalent addends problems (bottom graph) solved correctly on the posttest. Children are categorized according to the modality in which they produced the equalizer strategy during the instruction period. Producing a problem-solving strategy in gesture, as well as speech during instruction helps children retain and generalize the knowledge gained during that instruction period. Error bars represent standard errors.

Importantly, we see this same pattern no matter what type of instruction the children received. Table 2 presents the mean number of problems solved correctly by children in each of the five conditions in the study (for the six equivalent addends problems and six nonequivalent addends problems, i.e., the transfer problems). Children are categorized according to the modality in which they expressed the equalizer strategy during the instruction period. Note that, in each of the conditions, children who produced the equalizer strategy in speech and gesture during instruction solved more problems correctly than children who produced the equal-

TABLE 2
Mean Number of Problems Correct on Posttest as a Function of Experimental Condition and Child's Production of EQ During Instruction and Number of Children Who Contributed to Each Mean

Children Classified According to Their Production of the EQ Strategy During Instruction	*Experimenter Modeled EQ Strategy in Speech*				*Experimenter Modeled EQ Strategy in Speech and Gesture*					
	No Instructions to Copy		*Instructions to Copy*		*No Instructions to Copy*		*Instructions to Copy Speech*		*Instructions to Copy Gesture*	
	M	*n*	*M*	*n*	*M*	*n*	*M*	*n*	*M*	*n*
Equivalent addends problems										
Never expressed EQ	0.00	3	0.00	1	0.00	1	—	0	0.00	1
Expressed EQ in speech only	3.60	5	2.43	7	2.33	3	1.50	4	2.50	2
Expressed EQ in speech and gesture	5.50	2	2.50	2	5.50	6	4.67	6	4.83	6
Total	2.90	10	2.20	10	4.00	10	3.40	10	3.78	9
Nonequivalent addends problems										
Never expressed EQ	0.00	3	0.00	1	0.00	1	—	0	0.00	1
Expressed EQ in speech only	3.40	5	2.29	7	2.67	3	1.75	4	3.00	2
Expressed EQ in speech and gesture	6.00	2	3.00	2	3.50	6	4.17	6	4.50	6
Total	2.90	10	2.20	10	2.90	10	3.20	10	3.67	9

Note. EQ = Equilizer. Children are classified according to the modality in which they expressed the EQ strategy during the instruction period.

izer strategy in speech only during instruction, who, in turn, solved more problems correctly than children who did not produce the equalizer strategy at all during instruction. In contrast, experimental condition did not predict learning. In an ANOVA with condition as a factor and number of problems solved correctly as the dependent measure, we found no significant differences in posttest performance as a function of experimental condition: equivalent addends problems $F(4, 44) = .49$, *ns;* transfer problems $F(4, 44) = .35$, *ns.*

It is not particularly surprising that the experimental conditions in which we asked children to copy had no effect on posttest performance simply because our copying instructions didn't work—children who were told to copy gesture (or speech) behaved no differently during the instruction period from children who were not told to copy. Indeed, the only difference among groups during the instruction period was that children who saw gesture were more likely to gesture themselves. Children given instruction in Speech + Gesture were, in fact, more successful on the posttest than children given instruction in Speech alone (3.5 vs. 2.6 equivalent addends; 3.2 vs. 2.6 transfer problems), but these differences did not reach statistical significance. Thus, what really seemed to matter in predicting learning was not the instruction per se, but the effect that the instruction had on the children's performance during this period—in particular, whether the children gestured the equalizer strategy.

In this regard, it is important to note that only 4 children in the Speech condition produced the equalizer strategy in gesture, compared to 18 in the Speech + Gesture condition. Thus, the gestures that the instructor modeled did have an impact on the type of strategy the children produced in gesture. And, importantly, it was the type of strategy the children produced that best predicted learning—although producing some gesture was better than producing no gesture at all. In addition to the 22 children who produced an equalizer strategy in gesture during instruction, there were 19 who gestured during instruction but did *not* produce an equalizer strategy in gesture,[3] and 8 who did not gesture at all during instruction. In an ANOVA with type of gesture during training (no gesture, gesture but no equalizer, equalizer gesture) as a factor, and the number of problems solved correctly on the posttest as the dependent measure, we found a significant effect of type of gesture on posttest performance, $F(2, 46) = 12.21$, $p < .001$. Children who expressed the equalizer strategy in gesture and speech solved more equivalent addends problems correctly than children who gestured but did not produce the equalizer strategy in gesture or speech (equivalent addends problems: 4.5 vs. 2.7, $p = .06$, Tukey–Kramer; transfer problems: 4.1 vs. 2.8, *ns*), who, in turn, solved more equivalent addends problems

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[3] Of the 19 children who gestured but did not gesture an equalizer strategy during instruction, 8 produced a different correct strategy in gesture (e.g., grouping, add–subtract). These 8 children produced approximately the same number of correct solutions on the posttest as the 11 children who produced only incorrect strategies in gesture (5.4 vs. 5.7).

correctly than children who did not express the equalizer strategy at all during instruction (equivalent addends problems: 2.7 vs. .13, $p = .01$, Tukey–Kramer; transfer problems: 2.8 vs. 0, *ns*). Gesturing, and particularly gesturing a correct problem-solving strategy, leads to learning.

DISCUSSION

When given instruction in both gesture and speech, the children in our study reproduced the information conveyed in that instruction in their own gestures—and did so more often than when given instruction in speech alone. Indeed, children were just as likely to gesture a correct problem-solving strategy when they merely observed the teacher gesturing that strategy than when they were explicitly asked to copy the teacher's gestures. To our knowledge, this is the first demonstration that meaningful gestures produced by one member of an interaction can increase both the type and number of gestures produced by the other member. This finding is consistent with studies reporting that individuals mimic the nonverbal behaviors of their interlocutors in naturalistic contexts (Chartrand & Bargh, 1999).

Where our findings extend those of previous studies is that the behaviors imitated by the children in our study displayed a strategy that could be used to solve a second task. In studies of imitation in young children, the experimenter models a behavior and the question is whether the child learns to produce that behavior in the experimental context. The behavior may be directed toward a goal (e.g., lowering the head to touch a panel that turns on a light; Meltzoff, 1988) or not (e.g., protruding the tongue; Meltzoff & Moore, 1977). In both cases, the behavior to be learned is the behavior modeled by the experimenter.[4] Our study is unique in that we asked not only whether the child learned to reproduce the behavior that the experimenter modeled (her gestures), but also whether the child learned a second task, one that made use of the information displayed in the modeled behavior (how to solve the math problems). Of course, children could have imitated the form of the experimenter's gestures without understanding their meaning. But moving one's hands in imitation of the experimenter will not, in and of itself, solve the math problem. Copying the experimenter's hand movements can help children solve the math problems only if they understand what those movements stand for—that is, only if they understand what the gestures they imitate mean.

We found that they did. The gestures that children produced during instruction had an effect on how much those children retained from their instruction. Children who expressed a correct problem-solving strategy in gesture as well as speech dur-

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[4] As noted earlier, children will, at times, imitate the end product of an experimenter's actions but not the particular movements the experimenter used to create that product (e.g., Gergely, Bekkering, & Király, 2002).

ing instruction were significantly more likely to solve the math problems correctly on a posttest than children who expressed the correct strategy in speech alone or did not express the strategy at all. The gestures that the children produced during instruction thus appeared to have an effect on learning above and beyond the effect that their words had. These findings provide support for the hypothesis that adding gesture to instruction promotes learning, at least in part, because it encourages learners to produce their own gestures.

Interestingly, children in our study spontaneously increased production of the gestures that the instructor produced, but did not increase production further when explicitly asked to copy the instructor's gestures. Why? One possibility is that the copying instructions were too difficult for the children to follow. It may have been too demanding for the children to monitor their gestures while at the same time explaining how they solved the math problem. Gesturing is difficult to put under conscious control, even for adults. In addition, the children may have been confused by the instructions and therefore ignored them. It is unusual to draw attention to gesture and the children may not have understood the intent of the copying instructions. Finally, the children were not reprimanded for not following the copying instructions (although they were reminded of them on each trial) and may not have realized that they were not doing as the instructor asked. The children also did not increase the rate at which they imitated the instructor's speech when explicitly asked to copy it, although the most likely explanation for this finding is a ceiling effect (nearly all of the children produced the equalizer strategy in speech during instruction).

Because we did not succeed in getting *all* of the children in the Speech + Gesture condition to produce the equalizer strategy in gesture, it is possible that the children who chose to gesture the equalizer strategy were just those children who were particularly ready to learn mathematical equivalence in the first place. If so, gesturing might have been *reflecting* children's readiness-to-learn rather than playing a role in *causing* that learning. This is the least we can say: Gesture appears to be a reliable index of the nature of children's changing representations, one that is a more powerful predictor of lasting change than children's speech.

But, in fact, our findings allow us to go further. The fact that only 4 of the children in the Speech alone condition produced the equalizer strategy in gesture, compared to 18 of the children in the Speech + Gesture condition, suggests that our manipulation did shape the kinds of gestures the children produced during instruction. And it was the production of the equalizer strategy in gesture, not gesturing overall, that predicted greatest success on the posttest. Thus, the gestures that the children saw during instruction influenced the types of gestures that they themselves produced, which, in turn, predicted learning. These findings suggest that children's gestures may be playing a causal role in knowledge change, and that adding gesture to instruction is one way to elicit the gestures that can lead to that change.

Gesture appears to be an effective representational tool for learners (at least on math tasks). Note, however, that because no children gestured the equalizer strategy during instruction without also speaking the equalizer strategy, it is impossible to determine from these data whether gesture would have an effect on learning if it did *not* occur with speech. Indeed, the strong link between gesture and speech in all speakers (Goldin-Meadow, 2003; McNeill, 1992) would lead us to expect gesture to have an effect on learning *only* when produced in the context of speech. Spontaneous gestures nearly always occur with speech and, in fact, derive much of their potential for representation from the spoken context. Listeners are not very good at assigning meaning to gesture presented without speech, although they are better than chance (Krauss, 1991). Accordingly, it seems unlikely that gestures outside of the context of speech would be useful to learners. Nonetheless, our data leave open the possibility that they might.

Why might gesture be important for learning? Gesture conveys information visuospatially and, as a result, is able to highlight different aspects of a problem than speech. The spoken instructions that we used in our study contained components that varied from problem to problem (the references to the numbers in the problem), as well as components that were constant across problems (the statement that both sides of the problem need to be equal). In contrast, the gestures that we used took the same form on all of the problems (a sweep under one side of the equation, followed by the same sweep under the other side of the equation). These uniform gestures may have prevented the children from getting lost in the details of a particular problem and may have helped them focus their attention on the crucial elements of the instructions—that there are two sides to the equation and that those sides should be treated in the same way. Thus, the gestures we used may have been relatively easy to imitate because they were identical across problems; and they may have led to greater learning because they focused attention on the essential component of the problem-solving strategy.

As another possibility, gesture uses the body to do its representational work, and these embodied representations might promote learning. There is increasing evidence that embodied forms of representation are involved in cognitive processes, including working memory (Wilson, 2001), action memory (Engelkamp, 1998; Nilsson et al., 2000), mental imagery (Jeannerod, 1995; Kosslyn, 1994), and linguistic processing (Glenberg & Robertson, 2000; Richardson, Spivey, Barsalou, & McRae, 2003; Zwaan, Madden, Yaxley, & Aveyard, 2004). Gesture, as an embodied representational format, could preferentially engage any one or all of these four systems in contributing to learning.

First, gesture production is associated with a reduction in load on working memory systems; speakers remember more items (both verbal and visuospatial) when they gesture while explaining a math problem than when they do not gesture (Goldin-Meadow, Nusbaum, Kelly, & Wagner, 2001; Wagner, Nusbaum, & Goldin-Meadow, 2004). Gesturing while speaking thus eases the burden of speech production, providing a learner with additional cognitive resources that could be used to reflect on, and store, new representations. On this account, children who express their developing representations of a task in both speech and gesture take advantage of a representational format that is easier for them to produce, thereby freeing up cognitive resources that can be applied to learning the task.

Second, gesture production could directly change the online memory processes involved in storing new representations. There is a robust finding in the memory literature that performing an action enhances one's memory for that action—the *subject-performed task* (SPT) effect (Cohen, 1981; Engelkamp & Zimmer, 1984). Recent evidence suggests that sign language may engage the same mechanism. Hearing signers remember action phrases that they have signed better than action phrases that they have said, and the size of this effect is comparable to traditional SPT effects (von Essen & Nilsson, 2003; Zimmer & Engelkamp, 2003). Similarly, deaf signers remember action phrases that they have signed as well as action phrases that they have enacted, and both are better remembered than action phrases that were merely read (Zimmer & Engelkamp, 2003). These findings suggest that self-produced actions that are linguistic can be powerful memory cues. And, of course, gestures are self-produced actions occurring in a linguistic context. On this account, gesturing while speaking creates a more lasting representation in memory, which, in turn, facilitates learning.

Third, gesture production might encourage speakers to form imagistic representations that can later be accessed. McNeill (1992) argued that the act of gesturing and speaking influences speakers' online thought processes, and that gesturing, in particular, induces imagistic processing. Evidence from a variety of tasks suggests that gesture production is indeed associated with imagistic representation (Alibali et al., 2000; Hadar, Burstein, Krauss, & Soroker, 1998; Hostetter & Hopkins, 2002; Kita & Ozyurek, 2003). Children who observe and produce gesture might be particularly likely to form problem representations based on the mental image evoked by and associated with the gesture. And problem representations that are supported by both verbal and imagistic formats should be easier to maintain in memory than those supported solely by a verbal format (Clark & Paivio, 1991). On this account, gesture production encourages formation of an imagistic representation of a problem that complements and solidifies in memory the verbal representation of the problem, which, in turn, facilitates learning.

Finally, gesture perception and production might facilitate children's understanding of the relation between the problem in the world and their own mental model of the problem. Glenberg and Robertson (2000) argued that linguistic representations are supported by perceptually based mental models. Children who are exposed to gesture and who gesture might better represent the relations between objects in the world (the numbers and symbols in the physical problem), their mental models of the problem, and their understanding of the concept underlying the problem (Roth & Lawless, 2002; Roth & Welzel, 2001). On this account, gesture production encourages more developed and more accurate mental models of the problem and concept, sustaining deeper learning.

Whatever the mechanism, it is clear that including gesture in instruction encourages children to produce gestures of their own, and that producing one's own gestures is associated with learning. Children may thus be able to use their hands to change their minds.

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