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From action to abstraction: Gesture as a mechanism of change

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A R T I C L E I N F O

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A B S T R A C T

Piaget was a master at observing the routine behaviors children produce as they go from knowing less to knowing more about at a task, and making inferences not only about how the children understood the task at each point, but also about how they progressed from one point to the next. In this paper, I examine a routine behavior that Piaget overlooked – the spontaneous gestures speakers produce as they explain their solutions to a problem. These gestures are not mere hand waving. They reflect ideas that the speaker has about the problem, often ideas that are not found in that speaker's talk. But gesture can do more than reflect ideas – it can also change them. In this sense, gesture behaves like any other action; both gesture and action on objects facilitate learning problems on which training was given. However, only gesture promotes transferring the knowledge gained to problems that require generalization. Gesture is, in fact, a special kind of action in that it represents the world rather than directly manipulating the world (gesture does not move objects around). The mechanisms by which gesture and action promote learning may therefore differ – gesture is able to highlight components of an action that promote abstract learning while leaving out details that could tie learning to a specific context. Because it is both an action and a representation, gesture can serve as a bridge between the two and thus be a powerful tool for learning abstract ideas.

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In addition to his many other talents, Jean Piaget, the renowned developmental psychologist, was a superb observer. Piaget described the ordinary behaviors of childhood in exquisite detail, but his brilliance came in recognizing the significance of these behaviors for cognitive development. Piaget uncovered developmental milestones that have turned out to be robust across cultures and methods and, as a result, must be part of any comprehensive theory of ontogenetic change. As one well-known example, Piaget observed that, before age 7, children maintain that water poured from a tall, thin container into a short, wide container is no longer the same amount – these children are non-conservers. Once the ability to conserve liquid quantity has been mastered, children not only firmly believe that the amount of water does not change when it is poured, but they can provide coherent justifications for this belief. For example, to justify her belief in the conservation of liquid quantity, one conserver said, "Even though that one's taller and skinnier and that one's wider and smaller, they still have the same amount," thus making it clear that she understands how the height and width of the containers compensate for one another.

My goal is this paper is to focus on a behavior that Piaget saw, but did not consider significant – the spontaneous gestures that speakers produce when they talk. I argue that this behavior not only reveals important information about the steps learners take as they acquire a task, but also plays a role in facilitating those steps. The conservation task provides a nice illustration. The child just described, who justified her belief in the conservation of liquid quantity by describing how height and width can compensate for one another, gestured as she talked – she demarcated with her hands the width and height of the first (tall) container, and then demarcated the width and height of the second (short) container (see Fig. 1; Ping & Goldin-Meadow, 2008). This child conveyed compensation in gesture, thus reinforcing with her hands the salient aspects of her spoken explanation. Here gesture conveys approximately the same information as speech and, in this sense, can be safely ignored. But in the next example, gesture adds information to speech and thus enriches our understanding of the child's state of mind.

In this task, the child is shown two rows containing the same number of checkers; the checkers in one row are spread out, and the child is asked whether the two rows still have the same number of checkers. The child shown in Fig. 1, who had a firm grasp of conservation of liquid quantity, also understands conservation of number and says that the two rows still have the same number of checkers after one is spread out. When asked to justify her response, she says, "Because if we added them together, they would be the same number," an answer that relies on counting. At the same time, she displays a different principle in her gestures – the one-to-one correspondence between the two rows of checkers. She points at the spot where the first checker in row 1 was during the task; then at the spot where the first checker in row 2 was after the row had been spread out; then at the spot where the second checker in row 1 was; then at the spot where the second checker in row 2 was; and so on until she pairs up all of the checkers in row 1 with the checkers in row 2 (see Fig. 2; Ping & Goldin-Meadow, 2008). Her hands reveal knowledge (i.e., 1-to-1 correspondence between the rows of checkers) not found in her speech. In this instance, it does behoove us to take gesture seriously, which is my goal in this paper.

Gesture is an act of the body, and the body has been claimed to play a central role in cognition (e.g., Barsalou, 1999; Glenberg, 1997; Wilson, 2002; Zwaan, 1999). For example, previous motor experience can affect how language is understood and processed – playing hockey can enhance a person's ability to understand language about hockey, apparently because brain areas normally used to perform hockey-related acts become highly involved in understanding language about those acts (Beilock, Lyons, Mattarella-Micke, Nusbaum, & Small, 2008; see also Glenberg & Kaschak, 2002, Pulvermüller, 2005). The body not only affects how we interpret language, but also how we recall items and solve problems. For example, moving while encoding an action enhances recall of that action (Cohen, 1981; Engelkamp & Krumnacker, 1980; Saltz & Donnenwerth-Nolan, 1981), as does seeing someone else move (Cohen, 1981, 1983; Cohen, Petersen, & Mantini-Atkinson, 1987; Mulligan & Hornstein, 2003). As an example from problem solving, producing unrelated exercises between attempts at solving an insight problem affects solution times – adults who are given arm exercises that are compatible with the problem solution solve the problem more quickly than adults given exercises that are incompatible with the solution (Thomas & Lleras, 2009; see also Grant & Spivey, 2003; Thomas & Lleras, 2007).

Fig. 1. The gestures spontaneously produced by a child who is able to conserve liquid quantity when it is poured from one container to another. She displays an understanding of how the two dimensions of the containers compensate for another in her gestures by first indicating the thin width and tall height of container 1 (top two pictures) and then indicating the wide width and the short height of container 2 (bottom two pictures).

Although gesture is an act of the body, it is a special kind of act. It differs from many of the movements that have been explored in studies of embodied cognition in that it does not have a direct effect on the world. For example, producing a *twist* gesture does not, in and of itself, result in an opened jar; only directly twisting the jar lid can do that. If, however, someone sees the gesture, interprets it as a request for the jar to be opened, and complies, the gesture will have had an indirect effect on the world, and the effect will have been mediated by gesture's representational abilities. Here I ask whether gesture plays a central role in learning. Does the way we move our hands when we speak, movements that are typically ignored not only by researchers, but also by the gesturers themselves, affect how we learn?

In the first part of the paper, I provide evidence that gesture, when taken in relation to the speech it accompanies, can identify learners who are likely to profit from instruction on a particular task; in other words, gesture can be used to identify who is ready to learn. In the second part, I argue that

Fig. 2. The gestures spontaneously produced by a child who is able to conserve number when the checkers in one of two rows containing the same number of checkers are spread out. She displays an understanding of the one-to-one correspondence between the checkers in the two rows in her gestures. She points at the spot where the first checker in row 1 was (left-most picture), then at the spot where the first checker in row 2 was, then at the spot where the second checker in row 1 was, then at the spot where the second checker in row 2 was (right-most picture), and so on.

gesture does more than reflect the state of a learner's readiness to learn – it can play an active role in bringing about that learning. In the final part of the paper, I ask why. Gesture could bring about change because it is itself an action of the body and thus brings action into our mental representations. I provide evidence for this hypothesis but also suggest that it cannot be the whole story. Gestures are representational and thus more abstract than direct actions on objects. It may be this comfortable middle ground, with one foot in concrete action and one foot in abstract representation, that makes gesture such a powerful tool for learning.

Gesture can tell us who is ready to learn

The child portrayed in Figs 1 and 2 is a conserver – she understands that pouring water from one container to another does not alter the quantity of the water, and that spreading out a row of checkers does not alter the number of checkers in the row. Church and Goldin-Meadow (1986) studied 5- to 7-year-old children who were not yet able to conserve and found that they too gestured when asked to justify their beliefs in non-conservation. For example, one child says that the amount of water in the two containers is different because "this one's lower than that one," referring to the height of the water in speech while, at the same time, indicating the height of the two containers with her hands (Fig. 3, top pictures). This child is expressing the same information in speech and in gesture and has thus produced a gesture–speech match. Consider a second child who also believes that the amount of water has changed and also talks about the height of the containers in his speech. This child also gestures, but his gestures convey information that is different from the information he conveys in his speech – he indicates the widths of the containers in his gestures (Fig. 3, bottom pictures), and has thus produced a gesture–speech mismatch.

The children shown in Fig. 3 are indistinguishable if we do nothing more than listen to them. But if we look at their gestures, we find that we can predict which of the two children is more likely to profit from instruction in conservation. Church and Goldin-Meadow (1986) divided children into those who produced gesture–speech mismatches produced during a conservation pretest and those who

Fig. 3. Examples of two non-conservers explaining why they think the amount of water in the two containers is different. Both children say that the amount is different because the water level is lower in one container than the other. The child in the top two pictures conveys the same information in gesture as in speech (she indicates the relative heights of the containers) – she has produced a gesture–speech match. The child in the bottom two pictures conveys different information in gesture than in his speech (he indicates the relative widths of each container) – he has produced a gesture–speech mismatch.

produced only gesture–speech matches. They then gave all of the children the same conservation lesson, followed by a posttest comparable to the pretest. They found that children who produced mismatches before instruction were significantly more likely than children who produced only matches to improve on the conservation task after instruction (see also Ping & Goldin-Meadow, 2008).[1]

Is gesture–speech mismatch a reliable index of readiness-to-learn in other tasks and in learners of different ages? Perry, Church, and Goldin-Meadow (1988, 1992) asked 9- to 10-year-old children to solve mathematical equivalence addition problems of the following type, $6 + 2 + 3 = \_\_ + 3$. Children in the fourth grade in the United States routinely solve these problems incorrectly, either adding up all of the numbers in the problem and putting 14 in the blank (add-all), or adding up the numbers on the left side of the equation and ignoring the number on the right, thus putting 11 in the blank (add-to-equal-sign). When asked to explain how they got their answers, some children express the

[1] There are other types of non-gestural probes (e.g., a rating task, Garber, Alibali, & Goldin-Meadow, 1998; or a dual task, Goldin-Meadow, Nusbaum, Garber, & Church, 1993) that could be administered to the two children in Fig. 3 to distinguish between them. The fact that the two children are distinguishable (albeit not through their speech) suggests that the information encoded in the gestural component of a child's mismatch, even though not accessible to speech, is not tied exclusively to the child's hands.

same strategy in speech and gesture, “I added the 6, the 2, the 3 and the other 3 and got 14,” while pointing at the 6, the 2, the left 3, and the right 3 (add-all in both speech and gesture). These children are matchers with respect to the equivalence problems. Other children express a different strategy in speech and gesture, “I added the 6, the 2, and the 3 and got 11” (add-to-equal sign in speech), while pointing at all four numbers in the problem (add-all in gesture). These children are mismatchers. When both types of children are given a math lesson, children who were classified as mismatchers prior to the lesson are significantly more likely to improve after the lesson than children who were classified as matchers (see also Alibali & Goldin-Meadow, 1993).[2]

Producing gestures that convey information that is different from, but relevant to, the information conveyed in the accompanying speech is not a rare occurrence – it happens throughout the lifespan and in a wide variety of situations. Mismatches of this sort have been observed in toddlers going through a vocabulary spurt (Gershkoff-Stowe & Smith, 1997); preschoolers explaining a game (Evans & Rubin, 1979), counting a set of objects (Alibali & DiRusso, 1999; Graham, 1999) or assigning numbers to small and large sets (Gunderson, Spaepen, Gibson, Goldin-Meadow, & Levine, 2015; elementary school children explaining Piagetian conservation problems (Church & Goldin-Meadow, 1986; Ping & Goldin-Meadow, 2008), mathematical equations (Alibali & Goldin-Meadow, 1993; Perry et al., 1988), and seasonal change (Crowder & Newman, 1993); children and adults discussing moral dilemmas (Church, Schonert-Reichl, Goodman, Kelly, & Ayman-Nolley, 1995); children and adults explaining how they solved Tower of Hanoi puzzles (Garber & Goldin-Meadow, 2002); adolescents explaining when rods of different materials and thicknesses will bend (Stone, Webb, & Mahootian, 1992); adults explaining how gears work (Perry & Elder, 1997; Schwartz & Black, 1996); adults describing pictures of landscapes, abstract art, buildings, people, machines, etc. (Morrell-Samuels & Krauss, 1992); adults describing problems involving constant change (Alibali, Bassok, Solomon, Syc, & Goldin-Meadow, 1999; Alibali & DiRusso, 1999); adults narrating cartoon stories (Beattie & Shovelton, 1999a, 1999b; McNeill, 1992; Rauscher, Krauss, & Chen, 1996).

The mismatch between gesture and speech has been explored as a predictor of readiness-to-learn in a smaller number of tasks and ages, but here too the phenomenon has breadth. For example, toddlers who produce one word at a time and supplement that word with a gesture conveying additional information (e.g., “bottle” + GIVE gesture) are ready to move on to two-word utterances (e.g., “give bottle”), and do so more quickly than toddlers who complement their single words with gestures that convey the same information (e.g., “bottle” + point at bottle gesture; Iverson & Goldin-Meadow, 2005). As another example, elementary school children asked to reason about balance often express new ideas about the task in gesture before expressing these same ideas in speech (Pine, Lufkin, Kirk, & Messer, 2007). When given instruction in the task, these children are the ones most likely to benefit from that instruction (Pine, Lufkin, & Messer, 2004). A similar effect has been found in adult learners asked to predict which way the last gear in a configuration of gears will turn (Perry & Elder, 1997), or asked to draw the stereoisomer of a molecule (Ping, Larson, Decatur, Zinchenko, & Goldin-Meadow, 2015). In both cases, adults who display information in their gestures not found in their speech are particularly likely to make progress on the task after getting instruction in the task. Thus, when an individual of any age produces information about a task in gesture that is different from, but relevant to, the information produced in the accompanying speech, that individual seems to be in a state of cognitive instability with respect to that task and thus ready to profit from additional input on the task (a result that would not have surprised Piaget).

Interestingly, gesture–speech mismatch seems to be a better index of readiness to learn than other possible indices of learning that rely on the verbal channel alone. Church (1999) compared three indices that could be used to predict children’s readiness to learn conservation: number of pretest responses containing a gesture–speech mismatch (i.e., two different strategies, one in speech, one in gesture),

[2] Note that, in this type of mismatch, both of the strategies that the child produces (one is speech and the other in gesture) lead to incorrect solutions. This type of mismatch is, in fact, more common on mathematical equivalence problems than mismatches in which one strategy (typically in gesture) leads to a correct solution, while the other (typically in speech) leads to an incorrect solution. Interestingly, producing both types of mismatches predicts openness to instruction in mathematical equivalence (Perry et al., 1988).

number of pretest responses containing more than one strategy in speech (i.e., two different strategies, both in speech), and total number of different strategies conveyed in speech across the entire pretest. Each of these indices individually predicted learning from a conservation lesson, but when all three were included in the same model, the only significant predictor was gesture–speech mismatch.

One final point is worth mentioning. Gesture–speech mismatch predicts who will profit from instruction on a task in individuals who have not mastered the task. But, as we saw in Fig. 2, individuals who know how to solve a problem can, at times, convey information in gesture that is different from the information they convey in speech. Why would a person who has mastered a task produce mismatches? There are (at least) two reasons.

The first is that the learner may have only recently achieved success on the task and thus may still be in a transitional state. Perry et al. (1988) found that, after instruction, children who had learned to solve the math problems often continued to produce gesture–speech mismatches but, this time, the strategies they expressed in speech and gesture were correct. For example, for the problem $6 + 2 + 3 = \_\_+3$, the recent learner said, "I added the 6 and 2 and 3 and got 11, and 8 plus 3 makes 11, so 8 is the answer" (an equalizer strategy in speech), while pointing at the 6, the 2, the left 3, and then producing a take-away gesture under the right 3 (an add-subtract strategy in gesture); each of these strategies leads to a correct solution but by different routes. Before instruction, the strategies this child produced in her mismatches were either both incorrect, or one was correct (in gesture) and the other incorrect (in speech).

A second reason that an individual might produce gesture–speech mismatches on a known task is that the person may be responding to the discourse situation. Goldin-Meadow and Singer (2003) found that teachers instructing children who produced gesture–speech mismatches when explaining how they solved mathematical equivalence problems produced their own gesture–speech mismatches. But the teachers' mismatches differed from the children's in two respects: (1) The strategies the teachers conveyed in gesture and speech were both correct (as in the example just described). (2) The strategy that the teachers expressed in the gestural component of their mismatches could be found in speech on some other response; in other words, the strategy was accessible to speech as well as to gesture. In contrast, the strategies that the children expressed in gesture and speech were either both incorrect or only one was correct (in gesture) and the other was incorrect (in speech). Moreover, the strategy that the children expressed in the gestural component of their mismatches was found *only* in their gestures and not in their other spoken responses – that is, the information conveyed in gesture was accessible only to gesture and not to speech. Mismatch in a novice indicates that the mismatcher is able to simultaneously attend to more relevant aspects of a task than she can express in speech, or than she can integrate when computing an explicit judgment. These pieces of relevant knowledge put the mismatcher in a good position to benefit from subsequent instruction in the task.

There are thus systematic differences in the gesture–speech mismatches that novices and experts produce. The experts' mismatches reflect their ability to modulate their communication in response to the needs or skills of their partners. In contrast, the novices' mismatches reflect their own readiness for change and, as we will see, may even be an impetus for change.

Gesture can help us learn

The findings described thus far suggest that gesture can offer insight into the thoughts of learners as they transition from knowing less about a problem to knowing more. However, evidence is now mounting to suggest that gesture can play a causal role in bringing this transition about. Gesture can be part of the mechanism of change in two ways – the gestures that we see others produce can promote learning, and the gestures that we ourselves produce can promote learning.

The gestures we see can aid learning

To explore the impact that other peoples' gestures have on learning, Singer and Goldin-Meadow (2005) designed math lessons based on the teachers' spontaneous instructional strategies and used those lessons to teach groups of fourth graders mathematical equivalence. The instruction varied along two dimensions: (1) Some lessons contained only one spoken strategy (the equalizer strategy), others

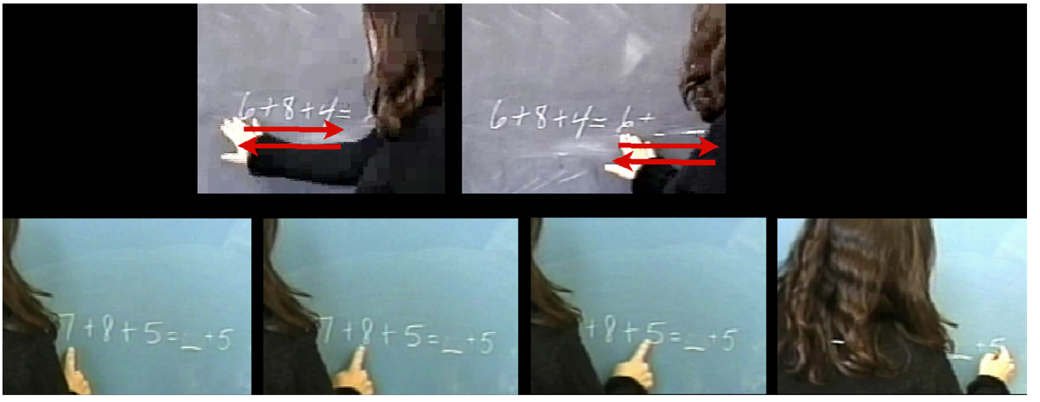

Fig. 4. Examples of the gestures that the experimenter produced in the matching gesture condition (top pictures) and in the mismatching gesture condition (bottom pictures). In both cases, the teacher produced an equalizer strategy in speech (see text).

contained two (the equalizer strategy and the add-substract strategy); (2) Some lessons contained gestures conveying a different strategy from speech (mismatching gestures), some contained gestures conveying the same strategy as speech (matching gestures), and some contained no gestures at all.

For example, in the matching gesture condition (Fig. 4, top pictures), the experimenter is teaching the problem 6 + 8 + 4 = 6 + __ and says, "The way to solve this problem is to add 6 plus 8 plus 4 which equals 18; we want to make the other side of the equal sign the same amount; 6 plus 12 also equals 18 so 12 would be the answer" (the equalizer strategy in speech). At the same time, she sweeps her hand first under the left side of the equation and then does the identical sweep under the right side of the equation, thus acting on each side of the equation in the same way (the equalizer strategy in gesture).

In the mismatching gesture condition (Fig. 4, bottom pictures), the experimenter is teaching the problem 7 + 8 + 5 = __+5 and gives the same equalizer strategy in speech, adjusting for the different numbers; she said, "The way to solve this problem is to add 7 plus 8 plus 5 which equals 20; we want to make the other side of the equal sign the same amount; 15 plus 5 also equals 20 so 15 would be the answer." However, she produced an add–subtract strategy in gesture – she pointed at the 7, the 8, and the 5 on the left side of the equation and then produced a "take-away" gesture under the 5 on the right side of the equation, thus indicating in gesture that the numbers on the left should be added together and the number on the right subtracted from that sum.[3] This example illustrates the type of gesture–speech mismatch that an expert (in this case, a teacher) would be likely to produce (i.e., two different strategies each leading to a correct solution).

Singer and Goldin-Meadow (2005) found that children who were given two strategies in speech (equalizer and add–subtract) during the lesson solved significantly fewer problems correctly on the posttest than children who were given only one strategy in speech (equalizer; none of the children solved any problems correctly on the pretest). However, giving children instruction that contained these same two strategies was effective in promoting learning – but only when the two strategies were conveyed in different modalities, one in speech and the other in gesture (Fig. 4, bottom pictures); in other words, only when the two strategies were produced in a gesture–speech mismatch. Children who were

[3] When using the equalizer strategy to solve a mathematical equivalence problem, children typically rely on trial-and-error (and not subtraction) to arrive at a number that makes the sum of the right side of the equation equal to the sum of the left. For example, a child using the equalizer strategy to solve the problem in the text, 7 + 8 + 5 = __+5, would add up the numbers on the left and get 20, and then try to come up with a number that would make 20 when added to 5 (the number on the right side of the equation); children did not try to subtract 5 from 20 to get the answer when using the equalizer strategy. In other words, the equalizer strategy seems to be a distinct strategy, one that does not reduce to an add–subtract algorithm, for most children.

in the mismatching gesture condition solved significantly more problems correctly after instruction than children in either the matching gesture condition or the no gesture condition (Singer & Goldin-Meadow, 2005).

These results make it clear that the gestures learners see can have a positive effect on learning. But gesture can also lead learners astray. For example, a child solved the problem 7 + 6 + 5 = __+5 by putting 18 in the block. The teacher gave him feedback and told him that his answer was incorrect and that he arrived at this answer by adding the 7, the 6, and the 5 (an add-to-equal sign strategy). However, at the same time, the teacher pointed at the 7, the 6, the left 5, and the right 5, thus producing an add-all strategy in her gestures. In response, the child changed his answer to 23, the answer one gets by adding up all of the numbers in the problem. The child may have been led astray by his teacher's inadvertent gestures. The bottom line is that gesture is a powerful tool, one that not only promotes, but also interferes with, learning.

As an example from another domain, consider the way an investigator questions a witness. Conducting forensic interviews with children is a sensitive process because children are prone to suggestive influences and are often not verbally fluent (Bruck & Ceci, 1999; Ceci & Bruck, 1993; Poole & Lindsay, 2002). Interviewers are cautioned against asking leading questions precisely because questions of this type encourage witnesses to report incorrect details (Poole & Lamb, 1998). For example, asking a witness, "What color hat was he wearing?" tends to elicits hat responses whether or not the target was wearing a hat. A less leading approach is to ask an open-ended question, for example, "what else was he wearing?"

Broaders and Goldin-Meadow (2010) asked whether gesture influences the way a witness responds to a question. They brought a musician into a classroom and filmed the event so that they knew precisely what happened; they then interviewed children individually about what went on during the visit. Some of the questions they asked contained gestures that conveyed information not conveyed in the accompanying speech. For example, the experimenter asked, "What else was he wearing?" while producing a donning-hat gesture. This gesture had the effect of turning an open-ended question into a targeted question, and children responded accordingly. They gave "hat" responses to this question-plus-gesture just as often as they gave "hat" responses to the targeted question, "What color hat was he wearing?" An interviewer's gestures can thus serve as a source of information and, at times, misinformation that can lead witnesses to report incorrect details.

Broaders and Goldin-Meadow (2010) also found that their child witnesses spontaneously produced gestures of their own during the interviews. Interestingly, these gestures often conveyed substantive information about the event that could not be found anywhere in the child's speech. Someone who had access only to a written transcript of the interview would miss thus important information that child knew but, in this instance, expressed only in gesture. At other times, the children's gestures introduced information that was later reiterated by the interviewer. Here the interviewer might erroneously attribute the first mention of a piece of information to the interviewer when, in fact, the information had been introduced by the child, but in gesture and not in speech. These findings not only point to the need to attend to and document the gestures that are produced in investigative interviews, but they also underscore the impact that other people's gestures can have on the way we see the world.

The gestures we produce can aid learning

To explore the impact that a learner's own gestures might have on learning, we again need to manipulate gesture. Broaders, Cook, Mitchell, and Goldin-Meadow (2007) told children to gesture, that is, to move their hands while explaining their solutions to mathematical equivalence problems. They found that children told to gesture produced more new – and correct – ideas in their gestures than children told not to gesture and than children given no instructions about their hands. Interestingly, at the same time that the children were producing these correct ideas in gesture, they continued to solve the problems incorrectly and articulated incorrect problem-solving strategies in their speech. However, when later given instruction in how to solve the problems, the children who had been told to gesture were more likely to profit from the instruction than the children who had been told not to gesture (Broaders et al., 2007). Gesturing can thus brings out ideas, which were presumably present in the child's repertoire but had not been articulated; in turn, these newly articulated ideas can lead to learning.

Even more striking, we can introduce new ideas into children's cognitive repertoires by telling them how to move their hands. For example, Cook, Mitchell, and Goldin-Meadow (2008) made children sweep their left hands under the left side of the mathematical equation 3 + 6 + 4 = __+4 and their right hands under the right side of the equation during instruction. They found that these children were no more likely to learn how to correctly solve problems of this type than if they had been told to say, "The way to solve the problem is to make one side of the problem equal to the other side" during instruction. However, the children who moved their hands according to a prescribed script were more likely to retain their newly gained knowledge than children who did not move their hands during instruction (Cook et al., 2008). Telling children how to move their hands can introduce new ideas into their repertoires that are later retained.

But how does gesturing promote new ideas? Learners may extract meaning from the hand movements they produce. If this is the case, then learners should be sensitive to the particular movements they produce and learn accordingly. Alternatively, all that may matter is that learners move their hands. If so, they should learn regardless of the particular movements they produce. Prior to a math lesson, Goldin-Meadow, Cook, and Mitchell (2009) gave children hand movements and/or words to imitate. All of the children were asked to imitate the equalizer strategy in speech – "I want to make one side equal to the other side." One group was asked to imitate these words while producing movements that instantiated the grouping strategy for solving the problem (e.g., a V-hand placed under the 3 and 2 in the problem, 3 + 2 + 8 = __+8, followed by a point at the blank, Fig. 5, top pictures). Another group was asked to imitate the words while producing movements that instantiated a *partially correct* grouping strategy (e.g., a V-hand placed under the 5 and 7 in the problem 4 + 5 + 7 = __+7, followed by a point at the blank; the gesture highlighted grouping two numbers but focused on the wrong two numbers, Fig. 5, bottom pictures). The last group was asked to imitate only the words without any movements at all. The children in all three groups were then told to repeat their gestures and/or words before and after attempting to solve each problem during the math lesson. All of the groups received

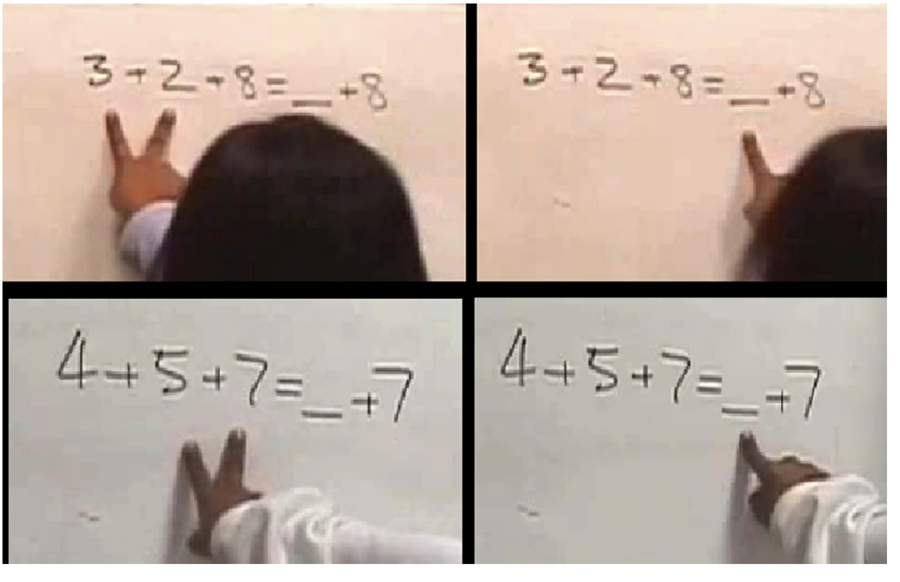

Fig. 5. Examples of the gestures that the children in the correct gesture condition (top pictures) and partially correct gesture conditions (bottom pictures) were taught to produce before and after solving each problem during the lesson. In both cases, the children produced the equalizer strategy in speech, "I want to make one side equal to the other side."

the same lesson – the experimenter taught the children how to solve the problems using the equalizer strategy in speech and produced no gestures at all.

Goldin-Meadow et al. (2009) found that children required to produce *correct* gestures during the lesson improved more from pretest to posttest than children required to produce *partially correct* gestures, who improved more than children required to produce *no* gestures. Importantly, this effect was mediated by whether children added the grouping strategy to their post-instruction *spoken* repertoires. Because the grouping strategy was never expressed in speech during instruction by either child or teacher, nor was it expressed in gesture by the experimenter/teacher, the information that children incorporated into their post-instruction speech must have come from their own gestures. Moreover, because children who were taught to produce the full correct gestures learned more than children who were taught to produce the partially correct gestures, we know that they were sensitive to the particular movements they produced (and not just to moving vs. not moving). One way gesturing can impact learning, then, is to focus attention on the meaning implicit in one's own hand movements.

Although the findings suggest that the children extracted information relevant to solving the problem from their hand movements, an alternative possibility is that the children's hand movements merely helped them focus their attention on the particular numbers that needed to be manipulated. Note, however, that the gestures children produced in the *partially correct* condition focused their attention on the wrong numbers (the 5 and the 7 in the $4 + 5 + 7 = \_\_ + 7$ problem). Nevertheless, children in this condition improved on the posttest, and did so more than children who did not gesture, making it unlikely that gesture's sole function was to regulate attention. Rather, the gestures that these children produced appeared to help them learn the grouping operation, as evidenced by the fact that they (like the children who produced fully correct grouping strategy) added grouping to their *spoken* repertoires after the lesson.

Gesture does not just reflect the incipient ideas that a learner has – it can play a role in helping the learner formulate and therefore develop these new ideas. In other words, the course of cognitive change is different by virtue of the fact that the learner has gestured. We may therefore be able to lay foundations for new knowledge simply by moving our hands. If this view is correct, even inadvertent hand movements have the potential to influence thinking, as has been suggested for children (Brooks & Goldin-Meadow, 2015) and adults (Chu & Kita, 2008) solving mental rotation problems.

Gesture as a mechanism of change

Gesture adds a mimetic representational format to the categorical format in language

Why does gesture promote learning? One possibility is that making use of two modalities at the same time strengthens the learner's representations of the problem, which, in turn, helps the learner take advantage of relevant input. Another possibility, however, is that it is not juxtaposing two modalities *per se*, but rather juxtaposing two different types of representational formats – a discrete categorical format found in speech and an analog mimetic format found in gesture (McNeill, 1992) – that promotes learning. For the most part, speakers gesture with the hands (but see Grenoble, Martinović, & Baglini, 2014; Shintel & Nusbaum, 2007, 2008; Shintel, Nusbaum, & Okrent, 2006), which means that we cannot distinguish between the two-modality vs. two-representational formats hypotheses.

However, deaf signers also gesture along with their signs (Emmorey, 1999; Sandler, 2003), and their gestures are produced in the same (manual) modality as their signs. These gestures are analog and mimetic, unlike the signs they accompany, which (like speech) are discrete and categorical (Klima & Bellugi, 1979). If juxtaposing different ideas across two modalities is essential to promote learning, then mismatch between sign and gesture (i.e., mismatch within one modality) should *not* predict learning in signers – only mismatch between speech and gesture (i.e., mismatch across two modalities) should predict learning. Alternatively, if juxtaposing different representational formats, regardless of modality, is key to promoting learning, mismatching gesture should then predict learning in signers as well as speakers.

Goldin-Meadow, Shield, Lenzen, Herzig, and Padden (2012) asked ASL-signing deaf children to explain their solutions to mathematical equivalence problems and then gave the children instruction in those problems. They found that the deaf children produced gestures on approximately the same proportion

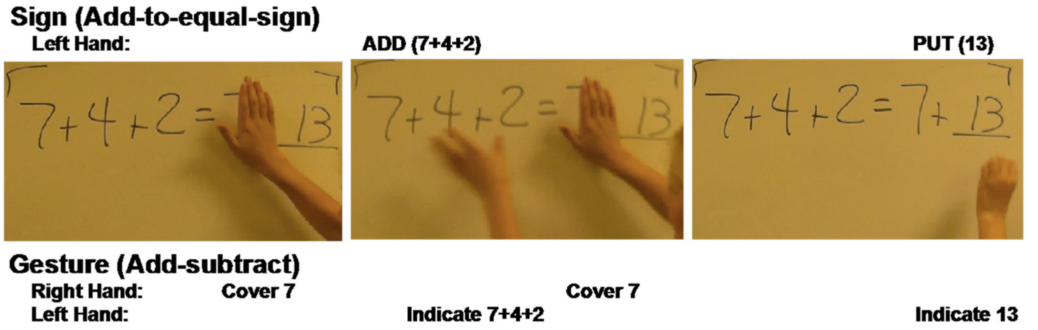

Fig. 6. An example of a gesture–speech mismatch produced by an ASL-signing deaf child. The signs are all produced by the left hand, an ADD sign combined with a PUT sign, which creates an "add-to-equal-sign" strategy (i.e., add 7, 4, and 2, and put the sum in the blank). The hand in the ADD sign is produced over a set of numbers and, as such, provides gestural information indicating those numbers (7, 4, 2); when we interpret this indexical information in the context of the gesture produced by the right hand, cover 7 ("take-away 7), we have an "add-subtract" strategy (i.e., add 7, 4, and 2, subtract 7, and put the sum in the blank).

of problems as the hearing children in the Perry et al. (1988) study. Moreover, the deaf children produced mismatches as often as the hearing children (see Fig. 6 for an example of a gesture–sign mismatch).

The crucial finding, however, is that the deaf children who produced many gesture–sign mismatches before instruction were significantly more likely to succeed after instruction than children who produced few mismatches. In fact, each additional mismatch produced before instruction was associated with greater learning after instruction. These findings make it clear that mismatch can occur within-modality, and suggest that it is the juxtaposition of representational formats (rather than the juxtaposition of two modalities) that gives gesture its power as a learning tool.[4]

We now know that gesture's effectiveness lies in its ability to add a second representational format to a learner's repertoire, rather than a second modality. But in all of the studies examining mismatch's ability to predict learning conducted thus far, the gestures have been produced in the manual modality. As a result, the findings leave open the possibility that gesture is effective because it is a manual action performed by the body. In the next two sections, I examine the implications of gesture's being an embodied action.

Gesture brings action into our mental representations

The gestures we produce when we talk might introduce action into our mental representations. Beilock and Goldin-Meadow (2010) explored this possibility using the well-known Tower of Hanoi task – individuals are presented with a stack of disks that vary from big to small on one of three posts; the individual's task is to move the disks one by one, without ever placing a bigger disk on a smaller one, so that the disks end up stacked in the same way on one of the other posts. Adults were first asked to solve the Tower of Hanoi problem with weighted disks (TOH1). The smallest disk in the tower was the lightest and could be lifted with one hand; the biggest was so heavy that it required two hands. The adults were then asked to explain how they solved the problem, gesturing while doing so. After the explanation, they solved the problem a second time (TOH2).

For some problem-solvers (*No-Switch Group*), the disks in TOH2 were identical to TOH1 and they, not surprisingly, improved on the task (they solved TOH2 in fewer moves and in less time than TOH1). For others (*Switch Group*), the disk weights in TOH2 were reversed – the smallest disk was now the

[4] Cross-mapping between representations has been proposed as a mechanism of conceptual change in other contexts; see Nersessian (1999) on model-based reasoning in the history of science, and Carey (2009) on bootstrapping as an explanation for discontinuities in conceptual development. Note, however, that metaconceptual control is likely to play a role in scientific change, but not in change brought about by gesturing.

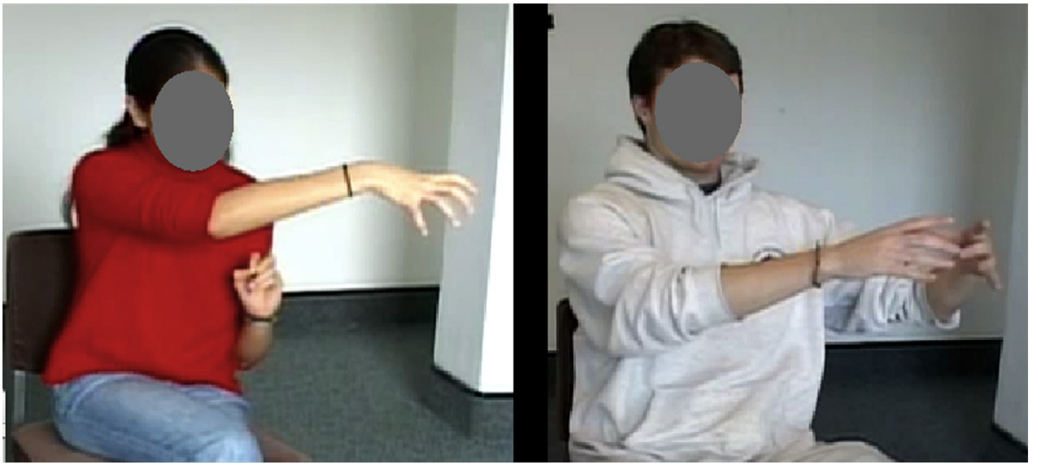

Fig. 7. Examples of two adults describing how they moved the smallest disk from one post to another in the Tower of Hanoi puzzle. The adult on the left produced a gesture with a one-handed grasp along with her speech, thus portraying the disk as light; the adult on the right produced a gesture with a two-handed grasp, thus leaving open the possibility that the disk could be either light or heavy.

heaviest and could no longer be lifted with one hand. This group did not improve and, in fact, took more moves and more time to solve the problem on TOH2 than TOH1.

The important point is that performance of the *Switch* group on TOH2 could be traced back to the gestures the adults produced during the explanation task. When the adults described moving the smallest disk, sometimes they would gesture the movement using one grasping hand (Fig. 7, left) and sometimes they would gesture the movement using two grasping hands (Fig. 7, right). The more an adult used one-handed gestures when talking about moving the smallest disk during the explanation, the worse that adult did on TOH2 (remember that the smallest disk on TOH2 in the *Switch* group could no longer be lifted with one hand). There was no relation between the type of gesture used during the explanation and performance on TOH2 in the *No Switch* group simply because the smallest disk on TOH2 could be lifted using either one or two hands.

The one-handed gestures speakers produced during the explanation task seemed to help consolidate a representation of the smallest disk as "light." This representation was incompatible with the action that had to be performed on TOH2 in the *Switch* group but not in the *No Switch* group. If gesturing is responsible for the decrement in performance in the *Switch* group, removing gesturing should eliminate the decrement – which is precisely what happened. In a second experiment that eliminated the explanation phase and thus eliminated gesturing entirely, the *Switch* group displayed no decrement in performance and, in fact, improved as much as the *No Switch* group (Beilock & Goldin-Meadow, 2010). Thus, the switch in disks led to difficulties on TOH2 only when the adults gestured in between the two problem-solving attempts, and only when those gestures conveyed information that was incompatible with the speaker's next moves.[5]

Disk weight is not a relevant factor in solving the Tower of Hanoi problem, and when speakers explained how they solved TOH1, they never talked about the weight of the disks or the number of hands they used to move the disks. However, it is hard to avoid representing disk weight when gesturing –

[5] Note that the task facing the Switch group after the disks were switched (i.e., TOH2) was jarring – weight was no longer correlated with size. However, the fact that the task was counter-intuitive cannot account for the switch effect simply because participants in the Switch group did not show a decrement on TOH2 when gestures were eliminated from the task; in other words, switching the disks did not, on its own, cause difficulties for participants – it was only after they gestured, and then only if they produced one-handed gestures that performance was affected.

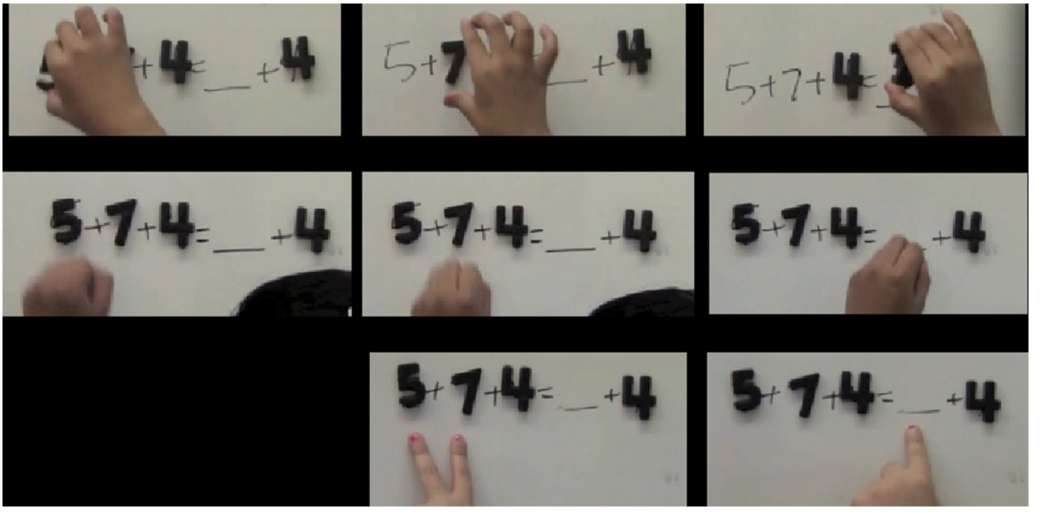

Fig. 8. Examples of the hand movements children in the three groups produced while saying, "I want to make one side equal to the other side." The child in the top pictures picked up the plastic 5 and the plastic 7 and held them over the blank (physical action condition); the child in the middle pictures mimed picking up the 5 and the 7 and holding them over the blank (concrete gesture condition); the child in the bottom pictures produced a V-point at the 5 and the 7 and then an index point at the blank (abstract gesture condition).

using a one-handed vs. a two-handed gesture implicitly captures the weight of the disk, and this gesture-choice had a clear effect on TOH2 performance. Moreover, the number of hands that the *Switch group* actually used when *acting* on the smallest disk in TOH1 did not predict performance on TOH2; only the number of one-handed *gestures* predicted performance. The findings suggest that gesture is adding information (presumably about disk weight) to the speakers' mental representation of the task, rather than merely reflecting previous actions. Gesturing about an action can thus solidify in mental representation the particular components of the task that are reflected in the gesture.

Interestingly, gesture was more effective than action in bringing task-relevant information into the adults' representations. Goldin-Meadow and Beilock (2010) compared two groups of adults, one who explained how they solved the problem while gesturing between TOH1 and TOH2 (the gesture group), and another who solved the problem again (the action group). They found that switching the disks resulted in poorer performance only for the gesture group and not the action group, even though both groups used one-handed moves (one-handed gestures or one-handed actions on the disks, respectively) equally often. Gesture was more effective than action in bringing weight information into the adults' mental representations of the problem (see also Trofatter, Kontra, Beilock, & Goldin-Meadow, 2014, who asked the action group to talk while moving the disks to make sure that the effect could not be traced to the presence of speech in the gesture group).

Gesture promotes generalization, action on objects does not

Why do learners benefit from gesturing during instruction? Gesturing could promote learning because it is itself a physical action. Alternatively, gesture could foster learning because it uses physical action to represent abstract ideas. To distinguish between these hypotheses, Novack, Congdon, Hemani-Lopez, and Goldin-Meadow (2014) taught 9- to 10-year-old children the grouping strategy for solving mathematical equivalence problems instantiated in one of three ways: (1) in the physical actions children performed on objects, (2) in concrete gestures miming those actions, or (3) in abstract gestures (see Fig. 8). The children were required to say the words, "I want to make one side equal to the other side," while producing the movements they were taught before and after solving each problem during the lesson.

Novack et al. (2014) found that, after the lesson, children in all three groups learned how to solve the problems on which they were trained (i.e., problems in which the blank was in the same position as the training problems, e.g., 6 + 2 + 4 = __+4). To solve these problems, the children could just follow a simple strategy instantiated in their actions – group the first two numbers, add them, and put that number in the blank.

Importantly, however, only gesture led to success on problems that required generalizing the knowledge gained. Children in both the concrete gesture and abstract gesture conditions transferred what they had learned to problems in which the blank was moved to the end of the right side of the equation, e.g., 6 + 2 + 4 = 6 + __. To solve these problems correctly, children would now have to follow a more sophisticated strategy – group the two numbers that do not appear on the right side of the equation, add them, and put that number in the blank. Pushing transfer even further, Novack et al. (2014) found that only children in the abstract gesture condition generalized what they had learned during the lesson to problems on which the grouping strategy could not be used at all, e.g., 6 + 2 + 4 = __+5. To solve these problems correctly, children had to have a principled understanding of mathematical equivalence, an understanding that they were more likely to gain if they had produced abstract gestures than either concrete gestures or actions during instruction. These results provide the first evidence that gesture can promote transfer of knowledge better than action.

Why does gesture promote learning and generalization?

When adults and children learn through self-produced actions on objects, they recruit sensorimotor regions that are reactivated when the learned information is subsequently processed (e.g., James, 2010; James & Swain, 2011). This reactivation likely underlies the beneficial effects that self-produced action has on learning (Prinz, 1997). In recent work, Wakefield, Congdon, Novack, Goldin-Meadow, & James (2014, 2015) found that a similar sensorimotor network is reactivated after children learn a problem through self-produced gesture. Wakefield and colleagues asked children to say the words, “I want to make one side equal to the other side” (the equalizer strategy), before and after solving each problem during a math lesson. One group said only the words; another group said the words while producing gestures conveying the same information (sweeping a palm under the left side of the equation and then doing an identical sweep under the right side of the equation).

Wakefield et al. (2014, 2015) then took only those children in the two groups who learned how to solve the problems and examined them while they solved comparable problems in the fMRI scanner – but this time without gesturing. They found that children who had gestured while learning how to solve the problems displayed significantly greater activation in a frontal-parietal sensori-motor network when solving the problems in the scanner than children who had not gestured during the lesson and had produced only speech (Wakefield, Congdon, Novack, Goldin-Meadow, & James, 2014, 2015). This finding suggests that the mechanism by which gesture facilitates learning involves establishing sensori-motor representations of the to-be-learned task; these representations are then reactivated when later solving the task without gesture.

But this cannot be the whole story. Reactivating sensori-motor (embodied) areas cannot fully explain why gesture facilitates learning simply because gesture and action are both embodied – but only gesture promotes generalization, action does not. There are (at least) two hypotheses, both of which could be correct, to explain the different impact that gesture and action have on generalization: (1) gesture could facilitate generalization by focusing learners on dimensions that lead to transfer; (2) action could hinder generalization by focusing learners on details that get in the way of transfer.

It is difficult to distinguish these two possibilities using behavioral data alone, but brain imaging studies offer a way to deepen our understanding of the mechanism underlying gesture’s impact on learning and generalization. If gesture’s ability to promote generalization better than action stems from the fact that it introduces abstraction into learning, we might then expect that children who learned through gesture will activate prefrontal regions, known to be recruited in higher-order thinking, while later solving comparable problems in the scanner, whereas children who learned through action will not. If this hypothesis turns out to be correct, we could encourage teachers to supplement gesture training with techniques known to promote higher-order thinking (e.g., analogy, alignment, comparison, Newcombe, 2010).

At the same time, gesture's superiority over action might come from the fact that acting on objects (but not gesturing about those objects) ties the knowledge gained to particular object-based contexts. If so, we might find that children who learned through action will activate object-processing regions when later solving the problems in the scanner, whereas children who learned through gesture will not. We would then have evidence that action gets in the way of generalization because it makes it difficult to transfer what has been learned to new situations. In this event, we might want to discourage action on manipulatives in the classroom or, in situations where it is preferable to act rather than gesture, encourage children to act on a variety of objects, thereby breaking the "tie" and making action more like gesture. By studying the neural level, we have the potential to gain insight into the mechanisms that underlie gesture's impact on learning and generalization. We can then use these insights to inform educators about best practices.

Conclusion

We have learned that the hand can play a role in learning, which probably would not have surprised Piaget, who considered representations to be interiorized actions (more precisely, interiorized imitations). Gesture could well be a mechanism underlying this process of interiorization, which is at the heart of developmental change in Piaget's (1945) theory.

Watching a teacher move her hands while giving a math lesson, or moving one's own hands during the lesson, makes success after the lesson more likely, particularly if the hand movements convey information that is different from, but relevant to, the information conveyed in the teacher's or one's own speech. But the important point that we have discovered about these hand movements is that they have a more powerful effect on learning when they do *not* have a direct effect on the world but instead represent the world; that is, when they are gestures.

Like actions on the world, gestures that represent actions promote learning a task on which the learner was directly trained. However, unlike action-on-objects, gesture also promotes transfer to tasks that require generalization of the knowledge gained. As a result, even though the mechanisms by which gesture and action-on-objects promote learning may overlap, they cannot be identical. Gesture may focus attention on components of an action that promote abstract learning while leaving out details that could tie learning to a specific context, allowing gesture to have a bigger impact on generalization and retention than action-on-objects does.

By examining the gestures speakers spontaneously produce when they talk, a behavior that has traditionally been below the radar not only for researchers but also for the speakers themselves, we have gained insight into the process of learning. Gesture is an action but it is, at the same time, an abstract representation. By providing a bridge between action and representation, gesture may be able to serve as a tool particularly well suited to learning abstract ideas.

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