The Cambridge Handbook of Cognition and Education

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9 Harnessing Our Hands to Teach Mathematics

How Gesture Can Be Used as a Teaching Tool in the Classroom

Elizabeth M. Wakefield and Susan Goldin-Meadow

The Body Plays a Role in Learning

The notion that the actions we perform with our bodies affect how we think and learn is not new. In the early twentieth century, Maria Montessori developed an educational philosophy based on the idea that children could better acquire knowledge by *actively* exploring the world around them rather than through traditional, verbal instruction (Lillard & Else-Quest, 2006; Montessori, 1995). Today, the Montessori approach is used in roughly 5,000 schools in the United States (Lillard & Else-Quest, 2006), as well as in many other countries around the world. In the mid-twentieth century, Jean Piaget (1952), famous for his work as a developmental psychologist, also focused on the importance of a child's motor exploration of the world for shaping cognition. He viewed cognitive development in terms of a stage theory in which children's actions – first, simple repetitive movements and, later, more complex explorative actions – play a role in the development of intelligence.

Both Montessori's and Piaget's frameworks highlight the importance of acting on objects to learn, especially in childhood. Building on these theories, a large body of research has shown that learning through producing one's own actions versus learning through observing others' actions *does* differentially impact how children think. For instance, physically manipulating a novel object (e.g., picking it up, turning it over, shaking it) will lead to better recall and recognition of the object than viewing these same actions produced by another person (e.g., Butler & James, 2013; Butler, James, & James, 2011; Harman, Humphrey, & Goodale, 1999). Many current educational techniques reflect these findings. For example, in mathematics classrooms, especially in early elementary school, teachers encourage children to interact with *manipulatives* when they are acquiring ideas such as quantity, addition, and subtraction (Mix, 2010).

Acting on objects is an important educational tool. However, focusing exclusively on actions that *manipulate* objects ignores another type of movement that teachers and students use in the classroom – gestures. Gestures are movements of the hands that can express ideas through their form and trajectory. In this chapter, we focus on the utility of gesture in educational practice, as gesture has been shown not only to reflect children's thought but also to *change* those thoughts (Goldin-Meadow, 2003).

Broadly speaking, gestures and actions on objects share a number of properties. Physically, gestures are movements of the hand that accompany speech and are, in this sense, actions. Functionally, gesture and action both shape cognition (e.g., Calvo-Merino et al., 2005; Casile & Giese, 2006; Chao & Martin, 2000; Cook, Mitchell, & Goldin-Meadow, 2008; Goldin-Meadow, Cook, & Mitchell, 2009; James, 2010; James & Atwood, 2009; James & Gauthier, 2006; James & Maouene, 2009; James & Swain, 2011; Longcamp et al., 2003; Longcamp, Tanskanen, & Hari, 2006; Novack et al., 2014; Pulvermüller, 2001; Singer & Goldin-Meadow, 2005; Wakefield & James, 2015) – hence their inclusion in a handbook on educational practice – and they may affect cognition in some of the same ways.

However, gesture also has some unique properties. Actions that are performed on objects have a direct effect on the world. In contrast, gestures that are performed off objects in the air do not bring about direct change. For example, twisting the cap of a bottle can directly open the bottle; gesturing a twisting motion over the bottle cannot. Actions complete a goal; gestures represent ideas. Because gestures are free from the constraints imposed on actions on objects, they are more flexible in their form. In gesture, we find a naturally used tool through which instructors and students can represent and manipulate ideas (e.g., Flevares & Perry, 2001) and, as will be reviewed later, a tool that shapes cognition when it is both produced and observed. Given these properties, gesture has the potential to be exploited in the classroom.

We begin by defining what gestures are and asking why they occur. We then review research showing that gesture can promote learning in classrooms, particularly in math classrooms. Studies of gesture use in naturalistic circumstances establish gesture's relevance to classroom teaching but they rarely provide enough leverage to argue that gesture has a causal effect on learning. We turn to laboratory studies to make the case that gesture promotes learning, both the gestures that students produce and the gestures that their teachers produce. We end with recommendations for educational practice and future directions for research.

How Do We Define Gesture and Where Does It Come From?

Gesture can be defined in many ways. At the most general level, gestures are movements expressed with the hands, arms, fingers, facial features, or even the entire body that communicate something to another individual (Crais, Watson, & Baranek, 2009). But it is often more useful to consider gestures within more specific categories. In a well-known categorization scheme, Kendon (2004) arranges gesture types on a continuum from movements completely independent of speech to those that are rarely produced in the absence of speech. Here, we focus our attention on one end of the spectrum: gesticulations that co-occur with speech. Gesticulations are either *imagistic* (iconic or metaphoric gestures) or *nonimagistic* (deictic or beat gestures). Imagistic gestures depict a shape, an action of some kind, or a movement pattern related to a referent (Kendon, 2004; McNeill, 1992). In other words, the form and/or movement trajectory of the gesture is meaningful in the context of the speech it accompanies. *Iconic gestures* represent concrete objects and actions through visuospatial representations. For example, an elementary school teacher, explaining the concept of a balance, might show children weights on opposite sides of the scale and then use her gesture to visually depict different ways the scale would shift, based on which side held heavier weights. The same gesture could be used when describing how to balance a complex equation in a high school algebra class. This second gesture would be an example of a *metaphoric gesture* because it expresses aspects of an abstract concept in a concrete, visuospatial manner (for discussion, see Cooperrider & Goldin-Meadow, 2017).

Unlike imagistic gestures, nonimagistic gestures single out referents or segment speech rather than iconically or metaphorically representing a referent (Kendon, 2004; McNeill, 1992). *Deictics* are pointing movements, with either the fingers or palm, that are used to indicate objects, locations, or other parts of conversation. *Beats* are rhythmic movements that are used to emphasize parts of a spoken sentence (McNeill, 1992). Essentially, these are the small movements that speakers will make that do not appear to represent the ideas they are communicating but often emphasize parts of the message. For the remainder of this chapter, we use the term "gesture" to refer to gestures that represent information through their form or indicate referents – iconics, metaphorics, and deictics.

There are different theories of how gestures arise but, in conceptualizing gesture as a special kind of action, the most useful framework through which to understand gesture production is the Gesture-as-Simulated-Action (GSA) framework (Hostetter & Alibali, 2008). The GSA framework is based on the theory that cognition is embodied (e.g., Barsalou, 1999): The way we understand the world and process information is grounded in our interactions with the environment. Cognition is thus based in reactivation of sensory-motor representations that have been built through previous sensory experiences. Hostetter and Alibali (2008) suggest that when these reactivations reach a certain threshold, activation "spreads" to primary motor regions and we produce overt gestures. Gesture, then, is the result of simulated actions (neural activation in premotor, motor, and sensory regions involved in motor planning or motor representations) that become realized as overt motor movements. According to the GSA framework, whether a simulated action gives rise to gesture is influenced by a number of factors. Gesture is more likely to occur if an individual is already engaging the motor system for speech production, which is one reason that we do not see spontaneous gestures occurring without speech. Gesture is also more likely to occur if the topic of our conversation is tightly coupled to a motor representation, either because we have motor experiences linked to this topic or because our language is tightly coupled to a motor representation. This prediction has been tested: Hostetter and Alibali (2010) demonstrated that participants were more likely to gesture if they were describing a pattern that they had physically created, as compared to a pattern that they did not create, supporting the tenants of the framework. Thus, gesture is an outward realization of our mental processes, expressing our thoughts through our hands. Given this framework, gesture lies at the intersection of action and thought, which makes it a powerful tool for education.

Gesture in Naturalistic Classrooms: Gesture Is There and Is Used

Why might gesture be useful in an educational setting and, in particular, when we teach mathematics? We focus our attention on math education for two reasons. First, students tend to struggle in math classes. Because mathematical concepts build on each other, once students fall behind, they have difficulty catching up in subsequent courses. Not only do delays of this sort decrease students' likelihood of succeeding in other STEM courses, but they also affect students' academic success more broadly (Adelman, 2006; Department of Education, 1997, 1999; Hansen, 2014). For instance, failure in algebra is predictive of failure to complete high school (Allensworth & Easton, 2005). Because success in mathematics is integrally tied to academic achievement, developing tools that will help children master mathematical concepts is important. A second reason for focusing on the utility of gesture in mathematics classrooms is that mathematics is the domain where the effects of gesture use have been most widely studied. We can therefore be confident in making recommendations for educational practice within the realm of mathematics. This focus on the benefits of incorporating gesture into the teaching and learning of mathematics may be historical – much of the gesture work in laboratory settings stems from two studies using mathematical concepts: Piagetian conservation (Church & Goldin-Meadow, 1986) and mathematical equivalence (Perry, Church, & Goldin-Meadow, 1988). However, these concepts became the focus of laboratory studies *because* researchers had observed natural use of gesture during instruction of these concepts. We argue that gesture is a useful tool in mathematics education because (1) practically speaking, educational practices based on student and teacher gesture can be implemented broadly, as gesture is naturally produced and universally accessible, regardless of the monetary resources available at a particular school; and (2) gesture is uniquely situated for expressing ideas that are integral to a mathematics classroom.

Implementing Gesture Instruction Is Feasible

A good teaching tool is one that can be implemented broadly. If a tool is difficult for educators and students to use, it is unlikely to be adopted. Likewise, if a tool is costly, it may not be accessible to schools in underprivileged communities – schools that are arguably in most need of good teaching techniques and student support. An important place to begin, then, in advocating for gesture as a teaching tool is to show that gestures are already in use in classrooms and that they can be easily encouraged without a major time commitment from instructors. Support for both of these ideas is found in classroom studies.

Although most research on gesture's effects on learning have been conducted in a laboratory setting, there is a small but growing body of literature documenting gesture's use in the classroom. Focusing on natural instruction in elementary and middle school, Flevares and Perry (2001) studied the use of nonverbal representations (e.g., pictures, objects, gestures) during instruction about place value. They found that, on average, teachers used five to seven nonverbal representations per minute and that the predominant type of nonverbal representation used in the classroom was gesture. This work has been corroborated by other classroom-based studies (e.g., Alibali & Nathan, 2012; Alibali et al., 2014; Richland, Zur, & Holyoak, 2007). Moreover, teachers spontaneously increase the amount of gesture during instruction when it becomes clear that students do not understand a particular concept in a lesson (Alibali, Nathan et al., 2013). In turn, students gesture spontaneously when asking questions or describing their solutions to problems, which can provide insight into their understanding of mathematical concepts (Alibali & Nathan, 2012). Together, these studies suggest that gesture is already used in classrooms by teachers and students, and that teachers are even more prone to use it when students are struggling with concepts.

Not only is gesture naturally used by teachers, but its use can easily be encouraged. Recent work has shown that teachers, when told about the importance of gestures for student learning, can intentionally increase the amount of gesture they use during instruction (Alibali, Young et al., 2013b). This study illustrates that a very simple intervention – telling teachers that gesture can help students learn – is enough to shape their behavior. Such an intervention would be quick and inexpensive, suggesting it could be implemented broadly, regardless of the financial resources of a school.

Gesture Can Make Complex Ideas Accessible

Part of understanding how gesture functions in an instructional setting comes from determining what gesture adds to instruction. Evidence for gesture's effects on learning in laboratory studies will be discussed in the next section, but observations in naturalistic classrooms can highlight ways that gesture is uniquely situated for expressing ideas that are important in a mathematics classroom. In general, an educator's goal is to communicate new ideas to students in a way that is accessible and will create long-lasting change in students' understanding of various concepts. In a mathematics classroom, students must learn overarching algebraic and geometric concepts, as well as strategies for solving problems that instantiate these concepts. Students must also learn how symbolic representations map onto abstract quantities and operational procedures, and how to move between different representational systems. In other words, they must be able to link abstract ideas to concrete symbols and apply arithmetic procedures to manipulate these ideas. In a review, Alibali and Nathan (2012) characterized the types of gestures used by instructors and suggest that gesture fulfills these functions when naturally used in mathematics instruction.

Pointing (deictic) gestures are the predominant form of gesture used during math instruction (Alibali, Nathan, & Fujimori, 2011). Teachers use points to link spoken instruction to concrete representations in the classroom or to link analogous elements within two or more representations. Classroom observations have revealed that linking ideas through pointing in conjunction with spoken instruction is more common than linking ideas through spoken instruction by itself. In fact, gestures are more often used when teachers link concepts or representations to each other than when they use other forms of narrative – in a sample of six teachers, Alibali, Nathan, and colleagues (2013) found that linking gestures were used 16.9 times per 100 words when teachers linked ideas together in speech, which is more than 1.5 times the frequency of gesture during storytelling (Alibali, Heath, & Myers, 2011).

This prevalent use of gesture suggests that teachers naturally find gesture to be a useful teaching tool and, indeed, linking gestures have been found to play important functions in classrooms. Linking spoken language to concrete representations in the classroom using points can elucidate or disambiguate spoken instruction that students find confusing or ambiguous on its own. For example, a teacher may point to the two sides of an equation, written on the board, when explaining the concept of mathematical equivalence with language such as, "We need to make the two sides of the equation equal to each other." Many students misinterpret an equal sign as an indication to add numbers together rather than as a symbol that separates sides of an equation. Thus, highlighting the sides of the equation with gesture may disambiguate the teacher's spoken instruction (Figure 9.1). When pointing is used to link analogous elements within two or more representations, it can help students move between different representational systems and integrate ideas into common mental representations. Alibali and Nathan (2012) provide an example of a teacher pointing to the short side of two different rectangles to show that these sides correspond to one another. Providing these gestures highlights a relation between the rectangles that may not have been apparent to students in the class, a connection that may need to be made before introducing an equation relating the two shapes.

In addition to points, teachers use iconic and metaphoric gestures in the classroom (Alibali & Nathan, 2012). Pointing gestures can create clear links between pieces of information but representational gestures can provide a visual depiction of abstract concepts being described in spoken instruction. Representational gestures therefore offer a second window onto these concepts. For example, in a naturalistic observation, a teacher illustrated how altering the slope of a line within an equation was represented in graphical form. First, the teacher pointed to the graphical representation of the two different slopes and the equations with the two different slopes – a linking gesture clarifying a relation. But then, the teacher went a step further, varying the angle of his outstretched arm to demonstrate slope changes using an iconic gesture (Figure 9.2). This physical embodiment grounds the abstract idea of slope in something more tangible for students. In a second example, a teacher explained balancing an equation and used metaphoric gesture to make an abstract concept concrete. The teacher talked about the elements on either side of the equation as spheres on two sides of a scale. She used gesture to "move" the spheres and showed how this affected the balance of the equation, making the concept more accessible to students by grounding instruction in the physical world and concrete experiences.

Gesture is thus used in the classroom during mathematics instruction by teachers and their students. But is there evidence that these gestures actually facilitate learning rather than their being a natural, but not relevant, part of instruction? Most evidence about the benefits of gesture comes from laboratory studies, but there is one naturalistic study that provides compelling evidence of gesture's power in the classroom. Richland (2015) analyzed ten videotaped fifty-minute

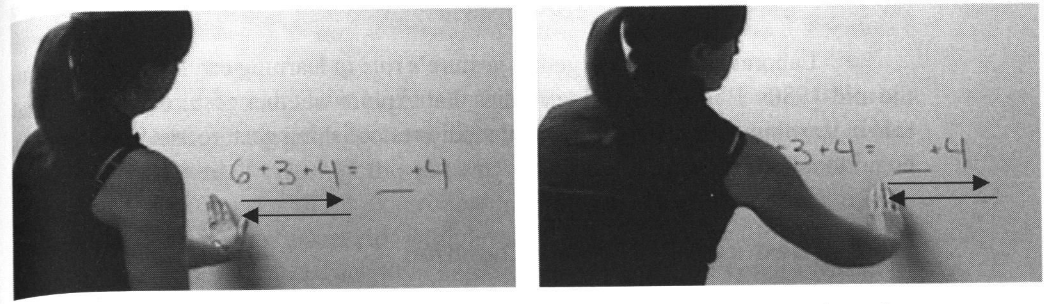

Figure 9.1 *Example of teacher highlighting two sides of an equation through gesture*

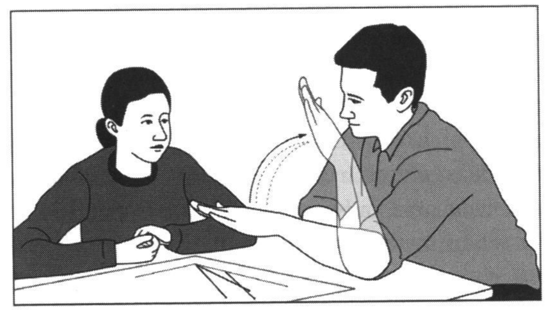

Figure 9.2 *Example of teacher demonstrating slope changes using iconic gesture (from Alibali & Nathan, 2012, with permission from Taylor & Francis)*

long classroom sessions from teachers instructing 8th grade children in the United States, Hong Kong, and Japan (thirty total), randomly selected from the Trends in International Mathematics and Science Study-Repeat (TIMSS-R). Both Hong Kong and Japan have significantly higher test scores in mathematics than the United States; the purpose of the study was to ask whether this difference corresponded to variations in how linking gestures were used during instruction. Richland found that, even though teachers from all countries used gesture in instruction, teachers from Hong Kong and Japan used significantly more linking gestures that physically displayed connections between two or more representations than teachers from the United States. Teachers from these Asian countries also displayed an increased tendency to adapt gesture to prior student knowledge, compared to teachers from the United States. For example, teachers in the Asian countries were more likely to use linking gestures for new concepts than for previously introduced concepts. These findings are consistent with the hypothesis that tailoring gesture to support mathematics understanding in classrooms can improve learning outcomes. We now turn to experimental evidence that gesture does indeed play a causal role in learning.

Gesture in Laboratory Studies: Gesture Promotes Learning

Laboratory studies targeting gesture's role in learning can be traced back to the mid-1980s. Before reviewing studies that explore whether gesture plays a causal role in learning, we turn to the original studies establishing gesture as a window onto cognition.

Student Gesture Is Relevant to Cognition

Much of the research on gesture and learning has involved manipulating teacher or student gesture and asking how these manipulations affect learning outcomes. However, initial work in this area focused on gestures that children *naturally* produce; gestures that were hypothesized to reflect a child's thought processes. Researchers asked whether teachers could use a child's gesture to identify when she was most likely to benefit from instruction on a particular concept, or, in more formal terms, when the child was in a *transitional knowledge state* (Church & Goldin-Meadow, 1986; Perry, et al., 1988).

From a Piagetian prospective, a transitional knowledge state occurs when a child holds inconsistent ideas about a concept, some incorrect and some correct, for which she previously held only incorrect ideas. A child is therefore at a point developmentally when instruction about the concept will be particularly beneficial because she is no longer committed to an incorrect understanding of a concept but has not yet embraced a new, more adult-like understanding (Perry et al., 1988). Consider a child who expresses an incorrect understanding of a concept in speech. Because gesture does not always convey the same information as the speech it accompanies (Goldin-Meadow, 2003), the gestures that the child produces have the potential to reveal a different understanding of that concept than is found in her speech. This general phenomenon (illustrated in Figure 19.3) – when gesture conveys different information from the speech with which it occurs – has been called "gesture–speech mismatch" (Church & Goldin-Meadow, 1986). In contrast, when gesture and speech express the same information, the response is called "gesture–speech match." A child who produces many gesture–speech mismatches when explaining how she solved problems probing a particular concept may be in a transitional knowledge state and thus ready to learn this particular concept.

To put the hypothesis that a child's gesture indexes whether she is in a transitional knowledge state to empirical test, Church and Goldin-Meadow (1986) and Perry and colleagues (1988) observed how many gesture–speech mismatches were produced by children explaining their solutions to problems with underlying concepts they had yet to master. They then asked whether producing many mismatches predicted a child's likelihood of learning from subsequent instruction in the concept. Finding that children who produced many gesture–speech mismatches before instruction have better learning outcomes than their peers who predominately produced gesture–speech matches would support the hypothesis that gesture reflects children's cutting-edge knowledge of a concept. If so, gesture can be used to identify children who are particularly ready to learn a new concept.

In both seminal studies (Church & Goldin-Meadow, 1986; Perry et al., 1988), children completed a pretest, instruction session, and posttest, while being video-recorded. During the pretest, children solved six problems and explained their solutions to an experimenter. Children between the ages of five and eight years were asked to complete Piagetian conservation questions related to number, liquid quantity, and length (Church & Goldin-Meadow, 1986), and children between the ages of ten and eleven years were asked to solve mathematical equivalence questions of the form $5 + 7 + 3 = \_\_\_ + 3$ (Perry et al., 1988). These age groups were chosen because these are the time periods during which children typically acquire an understanding of the respective concepts.

Children who answered all questions incorrectly on the math pretest and some questions incorrectly on the conservation pretest remained in the study and were given a standardized instruction session in which the researcher taught them how to solve problems similar to those they had just been tested on during the pretest. Children took an active role in the instruction session by working through problems with the instructor. Finally, children completed a posttest containing six problems in the same format but with new numbers for math, or the original six problems for conservation. Again, children were asked to explain their solutions to an experimenter. This protocol provided the template for experimental designs in subsequent studies.

In order to determine whether gesture–speech mismatch production before instruction predicted a child's learning outcome after instruction, children's explanations of their pretest problem solutions had to be coded. Researchers considered spoken and gestured explanations separately, so that coding a child's spoken explanation would not be influenced by the child's gestures, and vice versa. Each explanation was assigned a code based on the meaning it expressed. For example, when solving a mathematical equivalence problem such as $3 + 4 + 5 = \_\_ + 5$, a common mistake made by children at pretest was to answer "12." When explaining this solution, a child might say "I added up the 3, 4, and 5, and got 12." This explanation would be assigned an "Add-to-Equal Sign" code because the child's strategy was to add the numbers to the left of the equal sign to arrive at a solution. The gestures produced during this solution would then be considered separately, without the context of the child's speech. If a child pointed to the 3, 4, and 5 on the left side of the equal sign, and then the blank, this response would be assigned the same "Add-to-Equal Sign" code, as the gestures reflected this same strategy (Figure 9.3, Panel A). After spoken and gestured explanations were coded separately, the researchers considered the relation between the codes. In the example just given, the child's explanation would have been coded as a gesture–speech match, as the same strategy was reflected in both modalities. However, the researchers found that many children's gestures did *not* express the same strategy as their speech. Take, for example, a child who gave the same speech strategy "I added up the 3, 4, and 5, and got 12" but pointed at the 3, 4, 5, and the 5 on the right side of the equation. This gesture strategy would be assigned an "Add-All-Numbers" code, as the child's gestures indicate all of the numbers in the problem (Figure 9.3, Panel B). This explanation would have been coded as a gesture–speech mismatch because the information expressed in gesture was different from the information expressed in speech. An analogous system was designed for coding explanations given by children solving Piagetian conservation problems (Church & Goldin-Meadow, 1986). These coding systems have continued to be used in subsequent studies in which children were taught either conservation or mathematical equivalence.

Church and Goldin-Meadow (1986) and Perry and colleagues (1988) hypothesized that children who produced gesture–speech mismatches on at least half of their explanations of the pretest solutions (three or more out of six problems) – mismatchers – were in a transitional knowledge state. The next question was whether mismatchers respond differently to instruction than matchers, that is, than children who primarily produced gesture–speech matches (e.g., producing an incorrect "Add-to-Equal Sign" explanation in both gesture and speech when explaining a mathematical equivalence problem). Results from both studies indicated that children who were mismatchers before instruction showed significantly more improvement between pretest and posttest than children who were matchers before instruction. In addition, children who were mismatchers prior to instruction were more likely to successfully transfer the knowledge they had gained to similar, but not identical, problem types after instruction than children who were matchers.

(a)

(b)

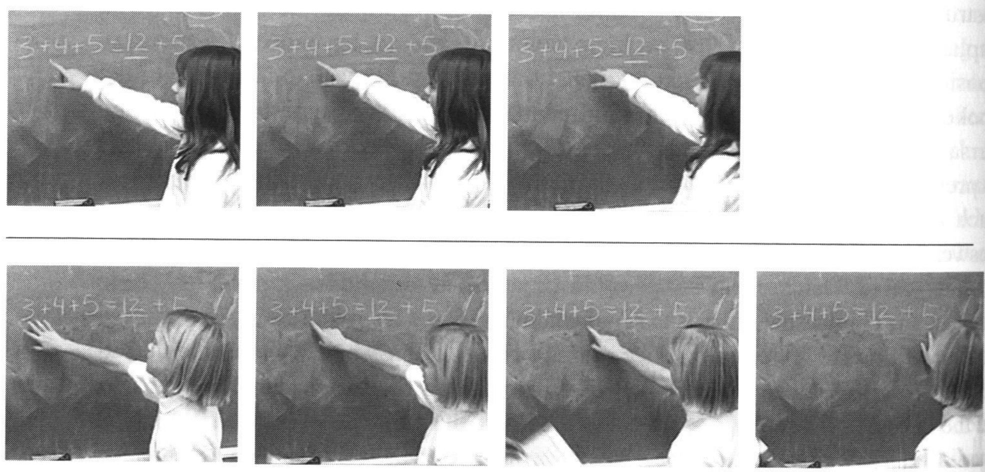

Figure 9.3 *Examples of gesture strategies produced by children*

(a) Add-to-Equal Sign. Child points to each addend on the left side of the problem.
(b) Add-All-Numbers. Child points to all four addends. In these examples, both children produced an Add-to-Equal Sign strategy in speech ("I added up the 3, 4, and 5, and got 12"). Thus, the child in panel (a) produced a gesture–speech match, and the child in panel (b) produced a gesture–speech mismatch.

These results suggest that producing gesture–speech mismatches on a particular problem can index whether a child is in a transitional state with respect to that problem.

The findings by Church and Goldin-Meadow (1986) and Perry and colleagues (1988) are of theoretical interest. However, it is not practical for teachers to video-record their students and code speech and gesture strategies in order to determine which children will benefit most from instruction before providing instruction. But, happily, it turns out that teachers and other adults *naturally* glean information from children's gestures (Alibali, Flevares, & Goldin-Meadow, 1997; Goldin-Meadow, Wein, & Chang, 1992). Alibali and colleagues (1997) asked adults to watch videotapes of children explaining their responses to mathematical equivalence problems; half of the children produced gesture–speech mismatches in their explanations, half produced matches. They then asked the adults to assess each child's knowledge about mathematical equivalence. Adults were more likely to mention strategies that the child had not produced in speech when observing mismatches than when observing matches. Moreover, many of these additional strategies could be traced to the mismatching gesture that the child produced. Interestingly, most of the adults said they were unaware that children were gesturing during the study.

But do teachers make use of the information that they glean from a child's gestures when deciding how to teach the child? The short answer is "yes." Teachers have been found to naturally modify their instruction in response to children who produce gesture–speech mismatches (Goldin-Meadow & Singer, 2003). Teachers were asked to teach six children how to solve mathematical equivalence problems. The teachers watched the children they were to teach as they explained their solutions to the pretest questions to the experimenter and then taught each child how to solve the problem. The teachers produced significantly more different strategies for solving the problem when teaching children who produced mismatches during the pretest or during the instruction period compared with children who never produced mismatches. This finding suggests that teachers are sensitive to the implicit knowledge a child expresses in gesture and that they adjust their instruction accordingly. If a child is producing mismatches on the math task, he or she is ready to learn that task and therefore should be able to take advantage of the additional strategies that the teacher produces. In contrast, a child who produces matches is not particularly close to a conceptual breakthrough on the problem and therefore may not have the capacity to benefit from relatively rich instruction. Thus, in a free-form, seminaturalistic instruction session, teachers are not only sensitive to whether a child produces gesture–speech mismatches but also change their teaching style in response to those mismatches.

These studies tell us that gesture can index a child's conceptual understanding and that teachers are sensitive to those gestures and alter their instruction accordingly. But they do not tell us whether gesture plays a *causal* role in changing thought. In other words, we know from these studies only that gesture is useful as a diagnostic tool to determine readiness to learn. The crucial question is whether incorporating gesture into a lesson, either by producing gestures that children can see or by asking children to produce gestures of their own, has an impact on learning. To address these questions, researchers use the same general experimental design (pretest–training–posttest) but add various manipulations. In some studies, the effect of teacher gesture on learning has been explored by designing teaching strategies that do, or do not, include various types of gesture and asking whether children's posttest performance varies accordingly. In other studies, child gesture is manipulated. Sometimes this manipulation is as simple as encouraging children to use their hands when they explain how to solve problems. In other cases, children are taught to perform specific gestures during training. In all cases, the dependent measure is the child's posttest performance. In the following sections, we consider (1) how a teacher's gesturing affects a student's comprehension of lesson material, and (2) how a student's gesturing affects how he or she processes the lesson material.

Teacher Gesture Has an Impact on What Students Learn

Teachers may change their style of instruction depending on a child's production of mismatches, but does this change affect learning? To address this question, it is essential to systematically manipulate whether gesture is included in a lesson. Overall, findings suggest that the gestures teachers produce facilitate student learning in preschool when children learn the concept of bilateral symmetry (Valenzeno, Alibali, & Klatzky, 2003), as well as in elementary school when children learn pre-algebraic concepts such as mathematical equivalence (Cook et al., 2008; Wakefield et al., 2018a; Singer & Goldin-Meadow, 2005). Students show more improvement from pretest to posttest when an instructor uses both gesture and speech strategies to explain a concept than when the instructor uses only speech strategies.

Research has also moved beyond showing that teacher gesture can help children learn to showing that the meaning expressed through teacher gesture affects what is learned. For example, teacher gesture has been found to be more powerful when it provides information not found in the teacher's speech, that is, when teachers use gesture–speech mismatches during instruction. In this case, the mismatches produced by a teacher provide two *correct* strategies, one in gesture and one in speech. These mismatches differ from the mismatches that signal a child's transitional knowledge state in that teacher mismatches contain two correct strategies whereas child mismatches contain at least one incorrect strategy, typically in speech. Singer and Goldin-Meadow (2005) conducted a study using a pretest–training–posttest design in which they manipulated the number of spoken strategies used by a teacher (one, two) and whether the spoken strategy was accompanied by gesture and, if so, the type of gesture (speech alone; speech and matching gesture; speech and mismatching gesture). Children taught with one spoken strategy performed significantly better at posttest than children taught with two spoken strategies. However, giving children two strategies in instruction could be effective, but only if one of the strategies was produced in gesture and the other in speech – that is, only if the instruction contained a gesture–speech mismatch. Children performed significantly better at posttest when taught with gesture–speech mismatches (where gesture and speech expressed different, correct strategies for solving the problems) than when taught with gesture–speech matches (where gesture and speech expressed the same correct strategy) or speech alone (see also, Congdon et al., 2017; Wakefield et al., 2018a). In fact, there was no significant difference between a child's performance after being taught with matching speech and gesture than with speech alone. Taken together, these studies suggest that gesture produced by a teacher may be particularly beneficial to students when it provides correct (and relevant) information *not* found in the teacher's speech.

It is important to point out that teacher gesture can be a powerful teaching tool even when it expresses the same information as the teacher's speech in both conservation (Church, Ayman-Nolley, & Mahootian, 2004) and mathematical equivalence (Cook, Duffy, & Fenn, 2013). For example, Cook and her colleagues (2013) created videotaped mathematical equivalence instruction in which the teacher stressed that two sides of the problem were equal to each other in speech. The teacher either produced this spoken strategy with no gesture (Speech Alone) or she produced the strategy while simultaneously underlining first one side and then the other side of the problem in gesture, a gesture–speech match (Speech + Gesture). Videotapes were shown to classrooms of students who completed pre- and posttests before and after instruction. Children who learned through instruction containing speech and gesture performed better than those who learned through instruction containing speech alone immediately after instruction and also after a twenty-four-hour delay. The children who saw the speech + gesture instruction also outperformed their peers on a more difficult test, one in which they had to solve multiplication problems of the same structure instead of addition problems. These studies bridge laboratory and school studies by showing that controlled instruction can be used at a classroom level to facilitate learning. Although this work supports using gesture that expresses the same information as speech in instruction, there is one caveat – the instruction in these studies was videotaped, and recent work suggests that videotaped gesture instruction is more powerful than live instruction (Koumoutsakis et al., 2016). Further work is needed to establish whether gesture expressing the same information as spoken instruction is useful when produced live by classroom teachers.

Student Gesture Also Has an Impact on What Students Learn

If gesture is powerful in the hands of the instructor, it stands to reason that it may also be powerful in the hands of a learner. Both naturalistic observation (Alibali & Nathan, 2012) and early laboratory work (Church & Goldin-Meadow, 1986; Perry et al., 1988) demonstrate that children use gesture when explaining their solutions to problems. Subsequent laboratory studies have shown that encouraging children to move their hands while explaining their solutions to a problem, or telling them precisely which hand movements to make, facilitates learning.

Interestingly, teachers may be able to encourage children to gesture simply by using their own gestures. Cook and Goldin-Meadow (2006) found that when the teacher used gesture, students were more likely to gesture as they explained solutions to problems than when the teacher did not use gesture. These students who spontaneously increased their gesture use, presumably in response to their teacher's gesture use, performed better after instruction than their peers. But the students who spontaneously increased their gesture use in response to the teacher might have been ready to learn in the first place. Thus, although the findings show that teacher gesture can lead to an increase in child gesture, the findings do not definitely show that child gesture has an impact on child learning.

To circumvent this problem, Broaders and colleagues (2007) gave some children explicit instructions to gesture. Children were given six math problems and asked to explain their answers. They were then asked to solve and explain six more problems, and were divided into three groups: one group was told to move their hands while explaining their answers to this second set of problems; one group was told not to move their hands; and a third group was given no instructions about their hands. After explaining their answers, children were given instruction about the problems and then asked to complete a posttest. Children who had been told to gesture on the second set of problems prior to instruction solved significantly more problems correctly than children who had been told not to gesture or had received no instructions about their hands. Interestingly, many of the gestures that the children produced when told to gesture on the second set of six problems conveyed strategies that could not be found in either speech or gesture on the first set of six problems. Being told to gesture thus brought out implicit knowledge (knowledge not evident in speech) that seemed to help the children benefit from instruction. Asking children to gesture can thus have positive effects on learning outcomes.

Children also benefit from being taught specific gesture strategies. When children are taught to produce a gesture strategy, with or without an accompanying speech strategy, they show better learning outcomes than when they are taught to produce a speech strategy alone (Cook et al., 2008; Goldin-Meadow et al., 2009). For example, Cook and colleagues (2008) taught children to produce an equalizer strategy for solving mathematical equivalence problems through speech ("make the two sides of the equation equal"), gesture (a sweeping gesture under one side of the equation and then the other side of the equation), or speech + gesture. All groups improved in solving posttest problems immediately after repeating the strategy during training. However, on a follow-up test given three weeks later, only children who had produced gesture (with or without speech) during training retained their newfound knowledge. Gesturing can make learning last.

Children can thus benefit from being taught to produce correct strategies for solving problems either through gesture–speech matches (Cook et al., 2008) or through gesture–speech mismatches (Goldin-Meadow et al., 2009). No study has directly compared learning outcomes after children are taught to use a gesture–speech match versus a gesture–speech mismatch in mathematical equivalence. However, the impact of

producing matches versus mismatches has been assessed in a different domain – learning palindromes. A palindrome is a word or phrase that is read the same, whether read from left-to-right or right-to-left. For example, the words "mom" and "dad" are palindromes. Children were taught to produce a speech strategy ("A palindrome reads the same forwards and backwards") with either a matching gesture (sweeping the hand from left-to-right under a palindrome written on the board and then right-to-left) or mismatching gesture (pointing simultaneously to the first and last letter of the palindrome and then to the second and second-to-last letter, showing the symmetry of the spelling). Children benefited equally from these gesture strategies. Moreover, producing speech with either gesture strategy was more effective than producing speech without gesture (Wakefield & James, 2015). Future work is needed to determine how general this effect is and, in particular, whether it extends to concepts like mathematical equivalence (recall that, on the math task, mismatching gesture was more effective than matching gesture when it was produced by the *teacher*, Singer & Goldin-Meadow, 2005).

What We Know About Mechanism

To understand why gesture helps learners, we need to ask questions about mechanism. Gesture could facilitate learning by directing a child's visual attention toward relevant information. We know that even young infants will follow a pointing gesture and look at the indicated referent (Rohlfing, Longo, & Bertenthal, 2012), and that visually attending to a referent while it is being labeled positively predicts a young child's ability to remember that label (Yu & Smith, 2012). To determine whether guiding visual attention is the sole way that gesture affects learning, Goldin-Meadow and colleagues (2009) taught some children to point at the wrong numbers. One group of children were taught to place a V-shaped hand under the first two addends on the left side of a mathematical equivalence problem (the 3 and the 4 in the problem $3 + 4 + 5 = \_\_ + 5$) and then to point at the blank, a correct "grouping" strategy in gesture, while expressing an equalizer strategy in speech ("I want to make one side, equal to the other side"; Figure 9.4, Panel A). Another group was taught to point to the *second* and *third* addends (the 4 and the 5 in the problem $3 + 4 + 5 = \_\_ + 5$) and then to the blank, a partially correct "grouping" strategy in gesture, while expressing the equalizer strategy in speech (Figure 9.4, Panel B). This gesture strategy is partially correct because it conveys the notion of grouping in the V-shaped hand, and it also highlights the fact that there are two sides to the equation with the point at the blank; the strategy is incorrect in that it encourages grouping and adding the wrong two numbers. A third group was taught only the equalizer strategy without any gesture at all. If gesture serves *only* as an attentional cue, children taught the partially correct grouping strategy should perform significantly worse than the other two groups. However, this group outperformed children who learned through speech alone, although they did perform worse than children taught to use the correct grouping strategy. Children thus seem to be gleaning information not only from the V-point that directs attention to the numbers but also from the shape of the V (which encourages grouping) and the sequence of the gestures (which highlights the two sides of the problem).

(a)

(b)

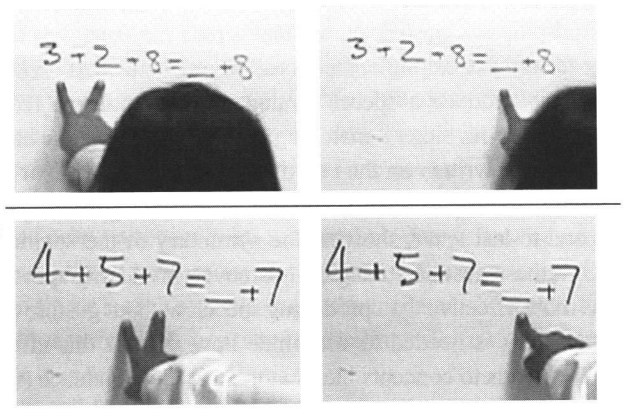

Figure 9.4 *Examples of the gesture strategies children were taught to produce in Goldin-Meadow, Cook, & Mitchell (2009)*

(a) Correct grouping strategy (b) Partially correct grouping strategy. In both cases, children were taught to produce the equalizer strategy in speech, "I want to make one side equal to the other side."

In a recent study using eye tracking technology, Wakefield and colleagues (2018a) asked about the effects of teacher gesture on children's visual attention during mathematical equivalence instruction. Two of the conditions in Goldin-Meadow, Cook, and Mitchell (2009) were adapted for this study – either children saw videotaped instruction in which the teacher expressed the equalizer strategy in speech alone or the teacher expressed the equalizer strategy in speech accompanied by a correct grouping strategy in gesture. As expected, children who received instruction that included gesture had significantly better learning outcomes than children who received speech-alone instruction. Using the eye tracker, the researchers also examined where the children allocated attention during the lesson and found that children who watched instruction with gesture allocated their visual attention differently than children who watched instruction without gesture – they looked more to the problem being explained, less to the instructor, and were more likely to synchronize their visual attention with information presented in the instructor's speech (i.e., they *followed along with speech*) than children who watched the instruction without gesture. But, as in Goldin-Meadow and colleagues (2009), Wakefield et al. (2018a) found that these differences in visual attention between groups could not fully explain gesture's beneficial effects. Even though the looking patterns characteristic of children in the gesture-instruction group predicted learning outcomes, the patterns did not *mediate* the effects of condition on posttest success. There was instead a complex relation between gesture and visual attention in which gesture *moderated* the impact of visual looking patterns on learning – *following along with speech* predicted learning for children who watched gesture instruction but not for children who watched speech-alone instruction. This study provides further evidence that visual attention plays some role in the effects gesture has on

learning but suggests that another mechanism may also be at play – gesture's ability to synchronize with, and supplement, information found in speech.

Throughout this chapter, we have considered how meaning expressed through gesture relates to meaning simultaneously expressed through speech. It may, in fact, be gesture's tight relation to speech that underlies its power in learning. We know that gesture has a privileged relation to speech in that it is synchronized, both temporally and semantically, with speech (Kelly et al., 2014; Kendon, 1980; McNeill, 1992). Because the two modalities can be produced at the same time, gesture has the potential to promote the integration of information conveyed in speech and gesture. In a recent study, Congdon and colleagues (2017) tested whether gesture is more powerful when the strategy it conveys is produced simultaneously with a different strategy conveyed in speech (S + G) than when the strategy conveyed in gesture is produced sequentially with a different strategy conveyed in speech (S→G) or when the two strategies are produced sequentially both conveyed in speech (S→S). Children in all three instruction groups showed the same improvement on the posttest problems that were identical in form to those taught during instruction. However, when children were asked to generalize what they had learned to problems with new forms, children who received instruction containing simultaneous speech and gesture (S + G) outperformed the other two groups (S→S and S→G). These children were also significantly more likely to retain what they had learned one day and four weeks after training than were the children in the other two groups. Although future work is needed to determine whether this finding holds when children are asked to produce the strategies themselves, the current work does suggest that part of gesture's power to promote flexible learning that can be retained lies in its inherent synchrony with speech.

A final property of gesture that may contribute to its ability to help children learn is that gesture brings the motor system into the learning process. At the beginning of this chapter, we reviewed evidence that cognition is embodied and that action affects thought. Part of the reason teachers use manipulatives in the classroom may be to give children active motor experience through which they can learn new concepts. Given that there are both similarities and differences between the motoric experience provided by actions on objects versus gesture, we can ask whether these motor movements have the same or different effects on how children learn.

In a neuroimaging study, Wakefield and colleagues (2014) found that children who produced both speech and gesture while learning mathematical equivalence showed significantly greater activation in sensorimotor areas when subsequently solving problems in the scanner (where no movement was taking place) than children who produced only speech during learning. The network of activation found in children in the gesture condition is similar to the network in children tested after they learned a concept through actions on objects (e.g., James & Swain, 2011). Learning through gesture has also been found to build sensorimotor representations in adults in a word learning paradigm (Macedonia, Muller, & Friederici, 2011). However, a study conducted by Novack and colleagues (2014) suggests that gesture can have different effects on learning than action on objects. Plastic numbers were placed on top of the numbers in a mathematical equivalence problem, which was written on a whiteboard.

In the gesture condition, children were taught to produce a V-point with their index and middle fingers under the 5 and 7 on the left side of the problem, and then point to the blank on the right side, instantiating the *grouping* procedure. In the action condition, children were taught to remove the 5 and the 7 number tiles and hold the two numbers under the blank, a concrete instantiation of the *grouping* procedure. Children in both groups produced these strategies while saying the equalizer strategy in speech as they attempted to solve each problem during the lesson. Gesture and action were equally effective in promoting success on posttest problems of the same form as the problems on which the children had been trained (3 + 8 + 7 = __ + 7), providing further evidence that motor experience in general can benefit learning. However, gesture also promoted success on posttest problems that required generalization (3 + 8 + 7 = 3 + __ and 3 + 8 + 7 = __ + 5) – action did not. The findings suggest that although recruiting the motor system overall promotes the learning process, producing movement that represents information (as opposed to manipulating objects) – that is, producing gesture – facilitates flexible learning that can be transferred to new problems. This finding has been conceptually replicated in a second domain, word learning, with younger children (Wakefield et al., 2018b), demonstrating that gesture can play an important role in generalizing new knowledge in a variety of domains. Future work using neuroimaging will explore whether learning through gesture versus action on objects leads to activation in different parts of the motor network (e.g., areas in the brain that are associated with abstraction for learning through gesture).

The studies that have been conducted to unpack how gesture shapes thought have begun to tell a narrative. It is likely that gesture is not powerful because of one property. Rather, gesture may be a powerful learning tool because it brings together in a single behavior a variety of skills that support learning.

Recommendations for Educational Practice

The reviewed literature suggests that gesture is a powerful educational tool that can facilitate children's understanding of mathematical ideas – both when it is performed by teachers and when it is performed by students. Iconic and metaphoric gestures can express difficult mathematical concepts in an accessible visuospatial format, and deictic gestures can link together concepts and representations as well as direct visual attention to relevant parts of an equation or diagram. Although most of the research on gesture's effects has been conducted one-on-one in controlled settings, gesture is spontaneously used in classrooms by both teachers and students and, in the few classroom studies that have been done, has been found to be effective. We can feel confident that teachers will be able to implement gesture-based educational tools in the classroom because they *already* use this tool, as do their students. We also know that gesture remains effective when we "scale up" from a single child to a classroom of children – Richland (2015) found evidence that, around the globe, teachers' use of linking gestures is associated with good student mathematics performance. And importantly, gesture is *free*, which means that teachers can take advantage of it as a tool regardless of the monetary resources available to them.

Before providing basic recommendations to educators about gesture use, we feel it important to mention a caveat: Gesture is a powerful tool, but as we learn more about its underlying mechanisms and the nuances of its effects, we also discover the boundaries of its benefits and places where other tools might be more effective. To illustrate this point, we consider two examples: (1) evidence that *doing* gesture may have a more powerful effect on learning than *seeing* a teacher gesture, and (2) evidence that there are times when actions on objects may be more useful to children than gesture.

If gesture is helpful because it involves the motor system in learning, children's own gesture might be expected to have a more powerful effect on their understanding of a concept than teacher gesture. Research in the action-learning literature has, in fact, shown that *doing* action has a more powerful effect on learning than *seeing* action (e.g., Butler et al., 2011; Harman et al., 1999; Kontra et al., 2015). Although the differences in doing versus seeing gesture have been relatively unexplored, one study of mental rotation has found that children *doing* gesture had better learning outcomes than children *seeing* gesture (Goldin-Meadow et al., 2012). Further research is needed, but the findings to date suggest that although teacher gesture is powerful, to get optimal effects, children should be encouraged to gesture as well.

There also may be instances when gesture is not the optimal tool to use. Although we have reviewed literature suggesting that gesture leads to more flexible learning than actions on objects, there may be times when children would benefit more from action experience than gesture. *Action* on objects may be more useful when children are first learning a concept because it is more concrete than gesture. Through manipulatives, students gain physical representations of concepts that allow them to offload some of the mental effort involved in learning (Lillard, 2005), and research has shown that this experience can be helpful to students (Kennedy & Tipps, 1994; Tooke et al., 1992). For children who are struggling with a new concept, manipulatives may provide a necessary foothold into the concept, allowing them to build a rudimentary understanding of the concept. This understanding could then be expanded through gesture. Indeed, there is evidence that being exposed to concrete instantiations of a concept before being exposed to a relatively abstract instantiation of the concept can, in some circumstances, promote learning. For example, Goldstone and Son (2005) found that having students manipulate displays that began as concrete and became abstract was a more effective teaching protocol than having them manipulate either concrete or abstract displays on their own. Thus, using action and gesture to complement each other may create an ideal learning situation for students. As the previous section makes clear, we are just beginning to understand the mechanisms that underlie the effects of gesture. By continuing this line of work, researchers will be able to make more specific recommendations about when and how gesture can be most effectively used for teaching and learning, transforming it from a relatively blunt hammer into a finely tuned instrument.

Even with the caveat that gesture may not always be the silver bullet in the classroom, ample evidence supports implementing gesture as an educational tool. Given that we know gesture can be used to facilitate student learning and is relatively easy to implement in the classroom, what are the next steps that will move gesture out of the lab and into the hands of teachers and their students? We share two basic recommendations that can be made on the basis of the current literature below.

Putting Gesture in the Hands of Teachers

It may seem obvious, but a first step in implementing gesture-based teaching strategies should be to teach educators the power of gesture for learning. We know that teachers adjust their instruction unknowingly, based on whether or not students express implicit knowledge about a new concept (e.g., Goldin-Meadow & Singer, 2003). We also know that if told to increase their gesture, teachers will do so (Alibali, Young et al., 2013) and will also alter their gesture use after instruction on how gesture promotes learning (Kelly et al., 2002). Thus, teachers who are aware of the role that gesture can play in changing the minds of their students are likely to move their hands during instruction. Teachers can be made aware of the utility of linking gestures for helping students integrate mathematical concepts and representations. Teachers can also be encouraged to think of ways to ground the concepts they teach in iconic and metaphoric gestures. A mathematics teacher knows more about the concepts she is teaching than gesture researchers do. If taught about how iconic and metaphoric gestures express information, teachers may realize they already have intuitions about gestures that could represent difficult concepts. These gestures could then be deliberately used in the classroom.

Putting Gesture in the Hands of Students

The gestures teachers make matter for student learning, but so do students' own gestures. Although designing specific gestures to teach to children (like the grouping or equivalence gestures used in math lessons discussed earlier) may be useful, an easy initial step would be to encourage children to reason out loud about problems and concepts they are learning and move their hands while doing so. Work from other areas shows that self-explanation can be a powerful tool in its own right (DeCaro & Rittle-Johnson, 2012; McEldoon, Durkin, & Rittle-Johnson, 2013). Combining it with gesture may be even better for a learner. Implementing this practice may not always be trivial. Often teachers must discipline students, so inviting them to talk and move around may seem counterintuitive. Yet what children do with their hands has the power to change how they think and, as long as gesturing is implemented in a way that does not disrupt the classroom, having students move may be a *good* thing.

Conclusions

In this chapter, we have provided evidence that gesture is a tool that can promote learning mathematical concepts. Because teachers and students naturally use gesture, it is an obvious tool to target and harness in the classroom. Based on current work, we suggest that teachers should be informed of the effects that different forms of gesture can have on students' learning outcomes

so that they can be mindful of using gesture in the classroom, and can encourage their students to use gestures of their own. Future work will help us understand *when* and *how* gesture promotes learning so that this continuously accessible tool can be put to optimal use.

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