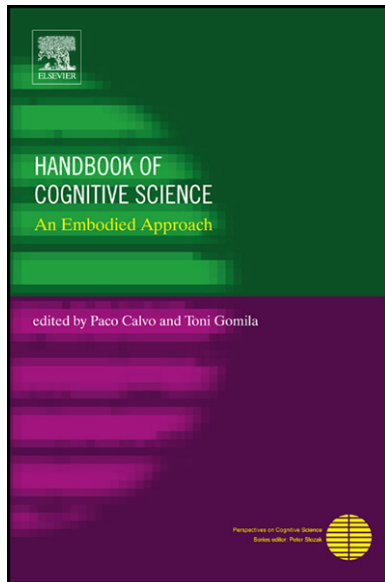


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# 18

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## EMBODIMENT FOR EDUCATION

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Watching a child makes it obvious that the development of his mind comes about through his movements ... Mind and movement are parts of the same entity.

...Maria Montessori (1967)

It is clear that one of the 20th century's greatest educational thinkers believed that there is a close connection between the body and education. But why should we think in the same line? The answer that I will develop in this chapter will be in two parts. After a brief discussion of embodiment theory, I will first briefly review data showing an intimate connection between the body and simple mathematics. Second, I will spend considerably more time reviewing data from a research project investigating a reading intervention based on an embodied theory of language. This intervention has been successfully applied across various populations of young readers, and we are beginning to explore its application in learning abstract concepts in science.

### WHY EDUCATION?

The essence of embodied theories of cognition is that the body, particularly bodily systems that have evolved for perception, action, and emotion, contribute to "higher" cognitive processes. Many of these cognitive processes are important to education, such as language comprehension, reading, mathematics, and scientific thinking. Thus, the classroom offers a fertile ground for observing effects of embodiment and testing theories.

But there is another reason for putting embodiment and education together. Consider why many modern societies have great belief in and respect for

science; because it works. For example, why do lay people think that physicists are pursuing something worthwhile? It is not because lay people have a clear understanding of esoteric theories; instead it is because modern physics has produced tremendous achievements that lay people can use, such as computers and television, as well as tremendous achievements that we can admire, such as traveling to the moon. Similarly, why do societies credit biological sciences? Because those biologists created amazing advances in healthcare. By analogy, what will lead societies to value cognitive science? It will be a demonstration of its practical applications, and those practical applications are likely to be in education. If embodiment theory can lead to the educational equivalent of a moon landing or a polio vaccine, it will demonstrate both its worth to society and the likelihood that it is the correct approach to understanding cognition.

## EMBODIED MATHEMATICS

There are good reasons to believe that there is a strong relation between embodied mechanisms and mathematics. Some of that research will be reviewed here (and see Chapter 7). Nonetheless, this section will be relatively brief because educational interventions for mathematics based on embodiment theory have not yet emerged.

## MATHEMATICS AND ACTION SYSTEMS

It is not a news that the hand is used by children in learning to count. But is the association between hand and number also found in adults? And, does the hand play a role in mathematical cognition, or is the association purely epiphenomenal?

The first question can be answered in the affirmative. Several reports using transcranial magnetic stimulation (TMS) have demonstrated a close relation between mathematical and motor processes in adults. TMS uses a hand-held electromagnet that is positioned on the scalp. When pulsed, the magnetic field penetrates the scalp, the skull, and outer parts of the cortex, and it thereby induces an electrical current in neurons. Repetitive application of TMS can be used to temporarily alter the functioning of the stimulated area. Single pulses, particularly in motor areas of the brain, can be used to measure how a cognitive task modulates cortico-spinal activity. For example, when the magnetic field stimulates areas of cortex that control the hand, measurable EMG activity can be recorded from muscles in the hand (and a strong enough pulse to the magnet generates overt movement). This EMG activity is referred to as a motor evoked potential (MEP). Thus, if a cognitive task modulates the MEP evoked by TMS, it can be inferred that the task influences motor areas of cortex (or more appropriately, the cortico-spinal system).

Andres et al. (2007) used TMS to uncover a relation between adult counting and the hand. In their experiments, participants either counted the number of dots in a

semi-circular array, or determined if two adjacent dots had the same color (control task). During the task, TMS pulses were delivered to hand, arm, or leg areas of cortex and MEPs were recorded from hand, arm, or leg muscles, respectively. They found that counting the dots (relative to the control task) increased MEPs measured in the hand, but not the arm or leg. Furthermore, a subsequent experiment ruled out the possibility that the effect was produced solely by subvocal articulation. Namely, mentally reciting numbers (without counting) did not affect MEPs.

The Andres et al. data clearly demonstrate an association between counting and motor system activity, particularly for the hand. Given that many children may learn to count by enumerating with their fingers, this result may not be very surprising. For this reason, Sato et al. (2007) chose a numerical task not easily associated with hand-based enumeration, namely parity (odd/even) judgments. Participants were shown single digits and responded orally with the parity. Shortly after presentation of the digit, a TMS pulse was delivered over the cortex controlling the left or right hand. The major finding was that right hand MEPs were affected by the parity task for small numbers. Thus, the data demonstrate that a mathematical task affects motor system even when there is no need for explicit counting.

Lindemann et al. (2007) also used the parity judgment task, but without TMS. Participants were required to make the parity judgment by grasping either a large (6 cm in diameter) wooden object using a power grip or a small (0.7 cm in diameter) object using a precision grip. The major finding was that parity judgments on large numbers were faster using the power grip, whereas the judgments on smaller numbers were faster using the precision grip. Thus again, it appears that there is a connection between the hand and simple mathematics in adults.

From the point of view of many theories of mathematical cognition (McCloskey, 1992; Anderson, 2005) the results are close to bizarre. That is, mathematics has been conceptualized as rule-like manipulation of abstract symbols that have no direct connections to perception or action. The data reviewed earlier indicate that this abstractionist account of mathematics must be wrong in at least some details. Nonetheless, one can still question if the embodiment effects are functional or not, and whether the action system is literally used in mathematical cognition, or do the effects simply reveal a residual activation of the hand based on early experience? Some evidence along these lines is presented in the next section.

## MATHEMATICS AND GESTURE

Several studies have demonstrated causal links between action, in the form of gesture, and classroom performance (see Nathan, in press for a thorough review). Perhaps the strongest of these is the study by Wagner Cook et al. (2008). In this experiment, children learned to solve problems such as  $4 + 9 + 3 = 4 + ?$  In one condition, children were taught a problem-relevant gesture (sweeping the hand under the left side and then the right side) to perform while solving the problem.

In another condition, the children were taught a verbal statement, "I want to make one side equal to the other." Four weeks later, children were tested again, and those who had been taught the gesture were significantly more likely to maintain learning gains than children who were taught the verbal statement.

### MATHEMATICS AND PERCEPTION

The abstractionist account of mathematics disavows connections between mathematics and perception as well as action. According to this account, perceptual systems are used to encode the mathematical information, but then the cognitive processes are independent of any perceptual information such as modality of presentation. Several research programs demonstrate that this independence is not found.

Campbell (1994) (Campbell & Fugelsang, 2001) presented the participants with relatively simple problems for solution (e.g.,  $3 + 4 = ?$ ) and verification (e.g.,  $3 + 4 = 8$ ), using either Arabic numerals or words (e.g., three + four = ?). As might be expected, given the differential size and familiarity of the stimuli, the word format resulted in people taking longer to solve the problems. More importantly, participants reported that more calculation was needed with the words, and that this became proportionally greater as the size of the numbers increased (Campbell & Fugelsang, 2001). In addition, Campbell (1994) found that people made different calculation errors with the two formats and that the two formats resulted in different patterns of priming from one trial to the next. Thus, perceptual format appears to affect not just peripheral encoding, but also calculation processes.

A similar conclusion was reached by Goldstone et al. (in press). In their experiments, participants judged if Equations [e.g., (18.1) and (18.2)] were correct. An important component of the judgment was the order of operations (e.g., multiplication before addition). This was explained to the participants and they were given feedback on their performance that depended on the participant's proper use of the order of operations. That is, there was no ambiguity regarding the task.

$$R * E + L * W = L * W + R * E \quad (18.1)$$

$$R * E + L * W = L * W + R * E \quad (18.2)$$

Both Equations (18.1) and (18.2) are correct, but participants found it easier to confirm this when the perceptual contiguity matched that order of operations, as in Equation (18.1), than when they mismatched as in Equation (18.2). That is, in Equation (18.1) the terms that are multiplied (e.g., R and E) are closely grouped and separated from the terms that should be added. In Equation (18.2), however, the spatial arrangement suggests that E and L should be processed together.

The grouping effect can be found even with quite subtle manipulations. Consider, for example, when the order of operations is consistent with

alphabetical proximity, as in Equation (18.3), or alphabetical proximity is inconsistent with the order of operations, as in Equation (18.4).

$$A * B + X * Y = X * Y + A * B \quad (18.3)$$

$$A * X + Y * B = Y * B + A * X \quad (18.4)$$

Participants were more likely to err when judging Equations such as (18.4). Again, the conclusion is that mathematical processing does not discard perceptual information.

In some ways, these studies are stronger than the TMS studies reviewed earlier. The TMS studies demonstrated that mathematical operations and actions are correlated, but not that action systems are literally used in doing mathematics. The Campbell and Goldstone studies do show a causal connection between perceptual format and mathematical problem solving.

All of these studies point to the same conclusion: Mathematics is not the cognitive manipulation of abstract symbols by rules. Instead, mathematical problem solving makes use of representations based on bodily systems of action and perception. Consequently, it seems reasonable to expect that teaching strategies that capitalize on the embodied nature of mathematics would be successful. To date, however, those strategies have not been developed and tested. The situation is different in the domain of reading comprehension, to which we turn next.

## EMBODIED READING

My approach to developing a reading intervention is based on an embodied account of language comprehension, the indexical hypothesis (IH; Glenberg & Robertson, 1999, 2000; Glenberg & Kaschak, 2002). According to the IH, three processes are used to understand a sentence. The first is indexing (mapping) words and phrases in a sentence to objects in the environment or perceptual symbols. Barsalou (1999) defines a perceptual symbol as a representation based on neural activity in perceptual areas of the brain. Thus, activating a perceptual symbol provides much the same information as that apprehended during experience with the relevant objects and events. For example, in the sentence "Art stood on the chair to change the bulb in the ceiling fixture," the phrase "the chair" is mapped either to an actual chair in the comprehender's environment or to a perceptual symbol of a chair.

The second process is deriving affordances from the indexed objects. Affordances are possibilities for interaction between a particular biological system and a physical situation (Gibson, 1979). Thus, kitchen chairs afford both sitting-on and standing-on for adults, whereas beanbag chairs afford only sitting-on.

The third process is meshing (integrating) the affordances as directed by syntax. The syntax of the example sentence indicates that "Art" is standing

on the chair rather than vice versa. The mesh process takes into account how affordances or actions can be combined while respecting biological constraints on action. Because a human can stand on a chair while holding a light bulb (i.e., the affordances can be meshed), the example sentence can be understood. Thus the processes of indexing, deriving affordances, and meshing the affordances ground the abstract language symbols (words and syntax) in a sensorimotor representation of what the language is about. This approach to language comprehension has received strong support (e.g., Glenberg & Robertson, 1999, 2000; Borghi et al., 2004; Chambers et al., 2004; Zwaan & Taylor, 2006).

The indexical hypothesis provides a rationale for why children have difficulty with symbolic information when reading—namely, the children have not learned to index *written* symbols to grounded representations. When children are learning a natural language, symbols are indexed and grounded immediately (Masur, 1997). For example, when a caregiver says to an infant, “Here is your bottle,” invariably (in the United States) the caregiver will point to or display a bottle. [Tomasello (2003) notes that explicit indexing for infants is not part of all cultures. However, mechanisms of joint attention ensure that the infant can induce the referents of many words.]

In contrast, when learning to read, children must concentrate on the (initially) laborious process of decoding print into sound. The objects read about are not in the environment and are rarely illustrated (and if illustrations are provided, reference to them is haphazard). Even when the child succeeds in pronouncing a word, the prosody may be so different from that in conversation that the laboriously pronounced word does not strongly activate appropriate perceptual symbols. For a child in this situation, reading becomes an exercise in naming ungrounded, and hence meaningless, symbols.

A similar analysis applies to older children (and adults) reading in unfamiliar domains (e.g., science). If the words are not adequately indexed, the material will be, at best, difficult to understand. Finally, the analysis holds for mathematical operations. To the extent that the numbers and symbols of mathematics are ungrounded, children will have a hard time understanding how those symbols can be applied in situations other than rote symbol manipulation.






To summarize, I propose that experience when learning a natural language leads to indexing of words, phrases, and grammatical constructions to objects and events, thereby grounding the symbols and imbuing them with meaning. In contrast, typical experiences in learning to read (e.g., concentrating on letter-to-sound correspondences) does not encourage indexing to objects and events, and may even work against it.

#### PHYSICAL AND IMAGINED MANIPULATION AS A READING INTERVENTION

Our intervention is designed to directly illustrate to young readers the indexing process, how comprehension flows from indexing, and to assist them in



Breakfast on the farm

Ben needs to feed the animals.  
 He pushes the hay down the hole.   
 The goat eats hay.   
 Ben gets eggs from the chicken.   
 He puts the eggs in the cart.   
 He gives the pumpkins to the pig.   
 All the animals are happy now.

**FIGURE 18.1** The farm toys and one text. The green traffic light signaled that a sentence was to be reread or used to direct manipulation. (See color plate)

developing skill at indexing. The procedure has two main components, physical manipulation (PM) and imagined manipulation (IM). With PM, children read a text about activities in a particular situation (e.g., on a farm), and toys representing the important characters and objects (e.g., a toy barn, animals, tractor, farmer) are simultaneously available (Figure 18.1). After reading a critical sentence, the child is cued (by the image of a green traffic light) to manipulate the toys to correspond to the sentence. This manipulation ensures that the words are indexed to objects, affordances derived (the child must manipulate the toys), and the concepts meshed to simulate the sentence. Thus, PM ensures grounding of the symbols. For young readers in the first and second grades, PM produces gains in recall and comprehension of 1.5–2.0 standard deviations compared to children who read and reread the texts without PM (Glenberg et al., 2004).

Substantial reading comprehension also materialized in additional experiments with second- and third-grade Native American learners (Marley et al., in preparation). PM can also be used in small reading groups in which one child reads a sentence and manipulates followed by a different child who reads the next sentence and manipulates (Glenberg et al., 2007a). In these reading groups, the gains hold for information from sentences that the child has manipulated as well as for information from sentences the child has watched others manipulate. Thus, the procedure is applicable in classrooms where it would be impractical to have toy objects for every child.

One might suspect that the theory would necessarily predict that children in the PM condition with literal interaction with the toys would outperform children who simply observed manipulation. However, recent work on the human mirror neuron system (Rizzolatti & Craighero, 2004) has demonstrated that action systems can be activated whether one takes literal action or simply observes action. Consequently, embodiment theory need not predict a difference between manipulation and observation conditions (although I will describe a subtle difference later).

Following PM, children are trained in IM by being asked to imagine manipulating the toys. With the very young children, the training requires them to describe what they imagine so that the researcher can correct misconceptions. Thus, children are corrected if they (a) simply repeat information in the sentence, (b) describe a mental image without describing actions, or (c) do not provide details about how an action could have taken place. (The overt description of the content of IM is required only during training, not during the application of IM.) We believe that this sort of training is more effective than having the child simply imagine a static situation (i.e., form a visual image of the situation).

We have found that IM leads to effects of comparable magnitude to PM, and that for the youngest children, IM can be used effectively at least 1 week after the child has used PM (Glenberg et al., 2004). Furthermore, for third-grade children, IM is effective for at least 2 weeks after initial training, and it can be applied to texts about situations with which the child has had no PM experience (Glenberg et al., 2007b).

### HOW IM WORKS

Both empirically and theoretically, IM following PM is different from simply providing visual information and instructions to make mental images. First, consider how PM works. Undoubtedly, part of the effect stems from the formation of visual and motoric representations in addition to a verbal one. These codes result in part from the process of indexing, as specified by the indexical hypothesis. Another reason PM works is that it forces the reader to consider how all of the parts of the sentence fit together. In brief, by requiring real action with real objects in real time, PM forces the reader to consider who did what to whom and when. This is the process of meshing (integrating) described by the indexical hypothesis. The success of IM, particularly following PM, trades on these processes, and is why IM is so effective, even compared to visualization strategies. For example, Marley et al. (in preparation) compared three conditions with third-grade, Native American English Language Learning (ELL) students. Two of the conditions were Reread and PM. The third condition was an Observe condition in which the children observed the experimenter manipulate the toys. When children literally manipulated or observed manipulation, children in the PM and Observe condition outperformed those in the Reread condition. When children were asked to engage in IM, however, only children who had previously engaged in PM outperformed those who observed the experimenter manipulating the toys.

Thus, IM is different from simply forming visual images in several respects. First, the instruction can be made very clear, because children are asked to imagine how they would act to create the situation, and these are actions that they have performed during PM. Second, to the extent that there is a close relation between language and action (as reviewed earlier), engaging the motor system will lead to a particularly appropriate type of encoding. Third, the images (visual and motoric) the child creates are dynamic, and thus capture many grammatical relations (e.g., who is acting on whom) and relations between narrative episodes. Finally, teaching IM appears to teach a skill, namely the skill of creating mental models from text.

### COMPARISON TO OTHER WORK ON CONCRETE MANIPULATIVES

A finding in much of the developmental and educational literature is that positive effects of concrete manipulatives are inconsistently obtained (Uttal et al., 1997; Uttal, 2003). In contrast, we have found that concrete manipulatives can lead to enormous benefits in reading comprehension as well as in some mathematical problem-solving contexts. There are three reasons why this contrast is more apparent than real. First, Uttal (2003) noted that when children are taught mathematics using manipulatives, they have a difficult time transferring that knowledge to written forms of representation. In our procedures, the manipulatives and the written information are combined, so that children can integrate the firsthand and second-hand knowledge (Schwartz et al., 2005).

Second, Uttal notes that concrete objects make for ineffective learning aids when children must treat the concrete object as a symbol—for example, when using a large block to symbolize 10 units. In cases such as this, children have a hard time dissociating the concrete uses of the object (e.g., that it can be stacked with other blocks to form a tower) from its symbolic use. When using PM and IM, the concrete manipulatives are not treated as symbols. Instead, the manipulatives are the physical situation to which the symbols (i.e., words) refer. Thus, when reading about animals on a farm, children using PM are reading about the particular farm toys that are in front of them. And when children are reading using IM, they map the words onto perceptual symbols learned from interacting with the farm toys. Similarly, when children are solving story problems about animals at a zoo, the problem is about the animals in front of them. In this way, the manipulatives are not symbols but they are ground.

Third, difficulties with the use of manipulatives have been investigated in the context of mathematics. In the main, PM and IM are procedures for enhancing reading comprehension. As far as I know, use of manipulatives in reading contexts has not lead to any difficulties in symbol use or understanding.

One might suspect that the use of PM and IM would lead to rather brittle knowledge. After all, how often do we have just the right toys in front of us while reading? However, our work demonstrates otherwise (Glenberg et al., 2007b). That is, once children have learned IM in a particular context, it is relatively easily

transferred to other domains. The reason appears to be that the combination of PM and IM teaches children the general skill of how to ground abstract symbols (words and mathematical symbols) in their experiences (i.e., to create embodied mental models).

### RELATION TO CURRENT EDUCATIONAL PRACTICE

Many classroom teachers already use manipulatives in teaching. Thus, how does the use of PM and IM differ from business as usual in the classroom? The first answer rests on the nature of the manipulatives. For example, Glenberg et al. (2007b) compared PM using story-relevant manipulatives (e.g., toy balloons in a fair scenario) to PM using abstract manipulatives (Lego pieces) which were meant to simulate the sort of counting aids used in many classrooms. Children in both conditions were given the same instructions—namely, to act out the mathematical story problem by counting, using the manipulatives. Nonetheless, children using story-relevant manipulatives outperformed the children using the abstract manipulatives. We believe that this effect arose because in the story-relevant condition the children were likely to use the manipulatives to create a representation of the problem world that constrained the mathematical operations. In the abstract-manipulatives condition, the children simply counted the Legos without any attempt to model the problem world. These findings are consistent with previous research that has demonstrated that the experience with different types of manipulatives can have differential effects on learning (Chao et al., 2000; Martin & Schwartz, 2005).

Perhaps most importantly, although manipulatives are commonplace during the elementary math lesson, they are rarely found during the elementary reading lesson. Thus the importance of PM and IM is that they promote skill in symbol manipulation in an area essential for learning, reading comprehension.

### PM AND IM WITH ENGLISH LANGUAGE LEARNING CHILDREN

Marley et al. (2007) demonstrated benefits of PM for listening comprehension for learning-disabled Native American children. Marley et al. (in preparation) extended this research to non-disabled, third-grade Native American children all of whom had been identified by their teachers as having limited English proficiency. The school district serving the children in this sample had not made adequate yearly progress, as defined by the *No Child Left Behind Act of 2001 (NCLB)*, since the enactment of the act. In addition, 88% of the children in the three elementary schools received free or reduced lunch.

Children were randomly assigned to Reread, PM, or an Observe condition in which the children observed the experimenter manipulate the toys. When children literally manipulated or observed manipulation, they outperformed children in the Reread condition. Using Cohen's  $d$  as a measure of effect size (i.e., the

number of standard deviations between the means of the two conditions), the differences are substantial, with  $d$ s = 1.12 and 0.84 for the contrast of Reread to PM and Observe, respectively. When children were asked to engage in IM, however, only children who had previously engaged in PM outperformed those who Reread, with  $d = 1.07$  (when toys were present during IM) and  $d = 1.08$  (when toys were not present during IM). These data illustrate the effectiveness of PM for ELL students, and the students' ability to transfer what they learned during PM to new stories using IM. In addition, the data demonstrate that for these unskilled readers, PM is needed to ensure the effectiveness of IM.

### PM AND IM AND VOCABULARY ACQUISITION

Reading consists of many processes in addition to comprehension. Children must learn the alphabetic principle, they must develop strong phonological skills, and they must develop fluency and a sight vocabulary. Thus, an important question is whether PM and IM interfere with the development of these other skills, or whether PM and IM might benefit the development of those skills.

To study the effect of PM and IM on vocabulary acquisition, the stories from previous reading experiments were adapted to contain two new pseudo-words each: one singular noun (e.g., "thrabe") and one present tense, third-person verb (e.g., "skigs"). Before reading a story, all children were introduced to both of the new words contained in the story: The experimenter pronounced the pseudo-words, used them in context, and used PM to define them. Then the children read and pronounced the words, read the words in context, and used manipulatives to act out sentences containing each new word.

Following the introduction to the new words, all children read a total of four stories (using PM or Reread) in each of two sessions. Thus, the experimental question is whether PM will result in better retention of the new words compared to the Reread control condition. At the end of both sessions, children were tested on item and action recognition. The children were shown the novel objects and actions and asked if they had seen the objects before and whether they remembered the names. Next, the children were asked to read a sentence out loud. Each sentence included one of the pseudo-words (in bold). After reading the sentence and pronouncing the word, the child was asked if the bold word made sense in the sentence (half of the sentences made sense based on the meanings learned) and why. At the end of the second session, they were tested on memory of word definitions, where the experimenter read a word, and the child stated whether it was heard before or not. When the child said "yes," the child was asked what the word meant.

Data from 31 second-grade children confirmed that children who practiced PM showed better comprehension for story events ( $M = 0.87$ ) than those who Reread ( $M = 0.72$ ). Also, children who manipulated were better able to determine whether a pseudo-word was used correctly in a novel sentence ( $M = 0.91$ ) than children who Reread ( $M = 0.85$ ). Finally, children assigned to PM were able to more accurately define words ( $M = 0.65$ ) than their counterparts who

Reread ( $M = .38$ ). In summary, the students in the PM condition were better able to remember story events, determine correct usage of pseudo-words, and define them in context, than the children who Reread. Thus, PM appears to be a useful tool for creating better memory for new words as well as supporting reading comprehension.

### PM AND IM IN SCIENCE EXPOSITION

Our previous work has demonstrated benefits of PM and IM for young children reading narratives. Is the technique also effective for older children reading exposition about abstract ideas? The answer is important for both theoretical and practical reasons. Theoretically, evidence for an embodied approach to cognition is strongest when applied to concrete concepts. Although there is some work extending the approach to more abstract ideas (Boroditsky & Ramscar, 2002; Richardson et al., 2003; Glenberg et al., 2008), the extent to which abstract concepts can be grounded in bodily experiences is still an open question.

The practical significance comes about because around the fourth grade, children experience particular difficulties in comprehending expository text (Armbruster & Anderson, 1988; Beck et al., 1997). Also, young readers face another challenge—the relative lack of expository or informational reading opportunities at the elementary level (Pressley et al., 1996; Morrow & Pressley, 1997; Duke, 2000) and a preference among teachers to select narrative texts for reading instruction (Donovan & Smolkin, 2001). Given that learning science, mathematics, and other content areas often rely on comprehension of expository text (Sweet & Snow, 2003), it is not surprising that many students are not up to these challenges. Thus, we have begun to explore the efficacy of PM and IM for understanding abstract expository text.

The application of PM and IM in exposition is based on research conducted primarily by Klahr and associates (e.g., Chen & Klahr, 1999; Toth et al., 2000; Klahr et al., 2001; Triona & Klahr, 2003) and a theoretical idea developed by Schwartz et al. (2005). Klahr has worked extensively with the control-of-variables strategy (CVS). CVS is the idea underlying experimentation, namely, that all (confounding) variables should be controlled to determine if the independent variable has an effect. Two important points that have emerged from Klahr's work are pertinent here: (1) PM is effective for learning CVS (although manipulation of pictorial representations on a computer screen can be equally effective) and (2) direct instruction on the CVS principle is more effective than pure discovery learning.

From Schwartz et al. (2005), we take the idea of the importance of combining firsthand (experiential) knowledge with secondhand (derived from language) knowledge. While recognizing the necessity of symbol grounding, Schwartz et al. also note that most formal learning is secondhand, mainly through reading. Hence, an important question is, how should firsthand and secondhand knowledge be integrated so that reading by itself becomes an effective mode for learning?

Our proposed answer is that PM provides the firsthand knowledge, and IM provides the skill needed to extend that knowledge to reading when physical objects are not available.

One additional idea is relevant for understanding the design of the experiment. Part of our explanation for the success of PM and IM is that children who are fluent in oral language use must, nonetheless, also learn to ground written words if they are to become skilled readers. This supposition that there is a difference between grounding heard words and written words is tested in the experiment.

In the experiment (Richmond et al., in preparation), we adapted the basic CVS design to answer the following questions: (a) When one is acquiring an understanding of CVS, how important is the opportunity to ground the written word (in contrast to the heard word)? (b) Is grounding necessary at all when learning an abstract principle, or are abstract principles better conceived of as rules operating on ungrounded symbols? (c) Will grounding of the abstract CVS concept during reading in one domain (e.g., how springs work) produce transfer when the children are reading to apply CVS in other domains (e.g., how plants grow)?

In the first of three sessions, fourth-grade children were given a brief oral introduction to CVS. Then, children read (or heard) texts that described how to set up experiments that conform to the CVS principle. Table 18.1 presents an example text, and Figure 18.2 illustrates one context, the ramps context, in which children carried out experiments to determine the factors that influence how far a ball will roll.

In the read and manipulate (RM) condition, children read aloud the texts describing how to set up the experiment, and they literally manipulated the experimental apparatus to conform to the text. In the listen and manipulate (LM) condition, the experimenter read the text aloud, but the children literally manipulated

**TABLE 18.1** Example of a text used to study the application of PM to the learning and application of CVS.

---

In this experiment, we will try to find out if the ramp surface makes a difference in how far the ball travels after leaving the ramp. Circle ramp surface on your worksheet.

- Ramp A surface should be smooth, and Ramp B surface should be rough.

Then, you need to be sure that all of the other variables (steepness, length, and ball type) are exactly the same for both ramps:

- The two ramps should both be steep.
- The two ramp lengths should both be long.
- The two ramps should both have a squash ball.

Now, record on your worksheet whether or not you think this is a good experimental design to test whether the ramp surface makes a difference in how far the ball travels after leaving the ramp.

- One squash ball should be placed on Ramp A, and the gate should be lifted.
  - One squash ball should be placed on Ramp B, and the gate should be lifted.
- 

Note: Children put a check mark in the box when the activity was completed.



**FIGURE 18.2** Ramps context for CVS. A confounded design is illustrated because the ramps differ in ball starting location, type of ball, ramp angle, and ramp surface. (See color plate)

the experimental apparatus. Note that the abstract information content is equated in these two conditions, but only in the RM condition do children have the opportunity to ground written words in their actions. Finally, in the read condition, children read the text aloud while the experimenter set up the experiment out of sight. In all conditions, after the experiment was set up, the children viewed the apparatus, observed the experiment and its outcome, and discussed again the CVS principle.

During the first session, children worked with two experiments in two of the three experimental contexts (e.g., ramps and how different types of objects sink). After an experiment was set up, but prior to conducting the experiment, the children were asked to explain and justify the experimental design (i.e., account for whether they think the design represents a “good test” of the focal variable). Then, the experiment was conducted, and children made observations of the outcome. Finally, the researcher changed the apparatus to set up confounded or noncontrastive (i.e., the same level of the independent variable was used in both conditions) experiment, and the researcher lead a discussion addressing why this was not a good experiment. The reason for this discussion was that learning the CVS principle involves not only the ability to design and execute unconfounded experiments, but also the ability to distinguish between confounded, unconfounded, and noncontrastive designs (Chen & Klahr, 1999).

Multiple types of assessments were used in the experiment. Here we report data from arguably the most important assessment, namely, how well children can set up unconfounded experiments and how well they can assess the experiments created by others. On the second day of the experiment, children were introduced to a third context for which they had had no previous experience. Table 18.2 presents the script used to introduce the “springs” context and an experiment that a child was asked to conduct. Each child (in the group of three) was asked, in

**TABLE 18.2** Introduction to the “springs” context and example performance assessment.

We will use these springs to test the effect of different variables on how long springs stretch. Just like with the ramps and sinking materials, there are four things you will test on the springs to see if they make a difference in how long a spring stretches. These four things are called variables and variables are things that can change. The variables for the springs are:

1. *Spring length* – the springs can be either short or long.
2. *Spring width* – the springs can have either narrow coils or wide coils.
3. *Wire thickness* – the springs can have either thin wires or thick wires.
4. *Weight size* – the weights that you hang from the springs can be either heavy or light.

Now, each you will have the opportunity to set up an experiment. You will read all of the texts, but only one person will set up the experiment. After that person has set up the experiment, the other two students in the group will decide whether or not they think he/she has set up a good experiment and record their decision on the worksheet (just as you did yesterday). You can also make a prediction about what you think will happen in the experiment. After the experiment has been conducted, you will complete questions 2 and 3 on the worksheet.

#### *Spring Experiment 1*

In this experiment, you will try to find out if the spring width makes a difference in how long springs stretch. Circle spring width on your worksheet.

The two springs should both be long.

The two springs should both have thin wires.

The two springs should both have light weights.

Before you do this experiment, record on your worksheet your reasons for why you have set up the experiment this way (*for the child conducting the experiment*).

*To other students in group:* Use this time to decide whether or not you think he/she has set up a good experiment. Circle your choice on the worksheet and then write a sentence below explaining your choice.

When you have finished writing, you can make a prediction about the experiment. Then, we will do the experiment and determine if the focal variable made a difference in how the experiment turned out.

turn, to create an experiment to test the effect of a variable (e.g., spring width) that had not yet been investigated, and the child was asked to justify the design. The other children in the group then evaluated the adequacy of design.

The means for the various measures reported next have been statistically adjusted to take into account effects associated with the eight classrooms from which the children were sampled. In addition, means are reported only for the first performance assessment in each group of three. Because the researcher and children continued to discuss CVS after each experiment, eventually children in all of the conditions came to produce unconfounded designs. How well did students design the experiment? The proportions of unconfounded designs were 0.91, 0.75, and 0.81 for the RM, LM, and Read conditions, respectively. The effect size ( $d$ ) for the statistically significant contrast between RM and LM was 0.78. When asked to justify the design, to what extent did children invoke

CVS (scored using a 0–4 rubric)? The mean scores were 2.10, 1.52, and 1.83 for the RM, LM, and Read conditions, respectively ( $d = .81$  for the RM to LM contrast). Finally, how accurately did the other children in the group evaluate the experiment? Based on the same 0–4 rubric, the means were 2.82, 2.18, and 2.15 ( $d = 1.01$  for the RM to LM contrast). In other words, the data consistently point to the success of children in the RM condition (which gave children the opportunity to index and ground written words) compared to the children in the symbolically equivalent LM condition and the Read condition.

These data lead to several important conclusions. First, the data suggest that PM can be of benefit when learning from exposition and applying abstract knowledge. Second, the data suggest that grounding written words is not automatic. Children in the RM condition had the opportunity to ground written words in their actions, and the benefits of that grounding become apparent when the children were required to read and interpret a new text (Table 18.2). Previous experience hearing the same texts in the LM condition was not as effective. Finally, the data demonstrate strong transfer. That is, children learned the CVS in two experimental contexts, but the performance assessments were conducted using a third, newly introduced context.

## CONCLUSIONS

If embodied approaches to cognition are on the right track, then they should provide key insights into educational processes. This chapter has surveyed two areas of promise, mathematics and reading comprehension. The work in mathematics suggests strong connections between the body and mathematical reasoning (Chapter 17). Nonetheless, this work has yet to produce effective interventions.

I have also provided an extensive overview of my own work applying an embodied approach to language comprehension to teaching reading comprehension. To date, the data are very encouraging. The PM intervention increases reading comprehension by 1 to 1.5 standard deviations over a Reread control. Importantly, once children have had experience with PM, they can engage in IM and thereby apply the strategy on their own. We have shown that the procedures can be applied to small reading groups, that they help with retention of vocabulary, and that they are effective when dealing with more abstract material such as CVS.

Are PM and IM the embodied educational equivalent of a successful moon shot? Clearly not. Nonetheless, the launching pad appears to be in sight.

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