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What Brains Are For: Action, Meaning, and Reading Comprehension

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The authors argue that brains evolved to control action, and, as suggested by M. Montessori (1967), a successful theory of cognition and its application will require recognition of that fact. The indexical hypothesis, an embodied account of language comprehension, posits that language is understood by simulating the actions that underlie sentence meaning and that reading comprehension can be improved by ensuring that this simulation occurs. Accordingly, first- and second-grade children manipulated toys (e.g., animals on a toy farm) to correspond to sentences in the stories that they were reading. Compared with children in a reread control group, manipulation improved memory and comprehension by almost 2 standard deviations. Similar improvements were found when the children were instructed to imagine the manipulation. In another experiment, manipulation and imagined manipulation produced a large increase in the ability of 3rd-grade children to solve some (but not all) mathematical story problems.

What are brains for? The answer to that question would seem to be obvious: Brains are for thinking! But consider some of the exquisite work that the brain does that one would not ordinarily classify as thinking. The brain controls and coordinates eye and neck muscles that allow us to track an annoying housefly (not to mention the tremendous amount of work done by the visual areas of the brain in locating and identifying the fly). The brain coordinates that tracking activity with reaching out with the hand and arm to swat the fly. Finally, the brain simultaneously controls and coordinates virtually every muscle in the body so that the path we walk will intersect the fly's trajectory while reaching with the arm and tracking with the eyes. It is a good bet that the brain coordinates control of movement much more frequently (and successfully) than thinking. Thus, the answer to the question "What are brains for?" might well be: Brains are for action!

The noted biologist Rudolfo Llinas puts it this way: "The nervous system is only necessary for multi-cellular creatures … that can orchestrate and express active movement" (Llinas, 2001, p 15). A particularly fascinating illustration of this fact is the life cycle of the sea squirt, a tunicate member of the phylum chordata (animals with spinal cords, including humans). The sea squirt begins life as an egg and then has a short existence (a few hours to a few days) as a tadpole-like creature with a primitive spinal cord, a brain, a light-sensitive organ, and the ability to express active movement. The sea squirt moves about until it finds a suitable attachment site, such as a rock. After attaching, the sea squirt never leaves; that is, it never again expresses active movement. The fascinating part of the story is that almost as soon as the sea squirt stops moving, it begins to ingest its brain! No action, no need for a brain.

Is the sea squirt simply an oddity, or does it have implications for human brains and human cognition? Of course, brains partake of many functions in addition to action, including thinking without expressing overt movement. Nonetheless, the notion that brains are for action provides an organizing theme, or inspiration, for conceptualizing cognitive functions that have been divorced from action in many contemporary theories. Thus, the plan for this chapter is to take the "brains are for action" theme all the way from the sea squirt to human cognition and then into the classroom. We begin with speculation about action and the evolution of cognition, and then we discuss the intimate connection between action and language comprehension. That connection leads to the development of a strategy to improve reading comprehension both when reading in the service of text comprehension and when reading to accomplish other tasks, such as mathematical story problem solving. Finally, we will discuss the practicality of transferring these ideas to the classroom.

ACTION, EVOLUTION OF COGNITION, AND MEANING

Imagine a chipmunk emerging from a hole in the ground to survey the environment. Upon seeing a threat, such as a snake, an effective action for the chipmunk is to dive back into its hole. If the chipmunk attempted to fly away instead, it would be consumed by the snake and not make much of a contribution to the gene pool. In contrast, suppose that it were a robin that sees the snake. Effective action for the robin is to fly away, whereas if it attempted to dive into a hole, it would be dead. Finally, effective action for a human who cannot fly or dive into a hole may be to flick away the snake with a long stick. Although cognition has surely advanced from the bird to the human, in all cases when the cognitive system is determining effective action it must take into account the body morphology of the actor. Thus, it is likely that there has been co-evolution of cognition and the body; that is, the evolution of one is constrained by the evolution of the other.

In addition to contributing to effective action, we also suppose that cognition is what makes meaning, or sense, out of the world. Is there any way in which action and meaning can be connected? Glenberg (1997) proposed that meaning is tied to action. Namely, the meaning of a situation to an individual (human or nonhuman animal) consists of the set of actions the individual can undertake in that situation. The set of actions is determined by the goal-directed mesh of affordances. The notion of an *affordance* was introduced by the perceptual psychologist James Gibson (1979). The term captures an interaction between body morphology and the physical environment. That is, what can be done with a physical object, such as a chair, depends on the body of the animal interacting with it. (See Glenberg, 1997, for an extension of the Gibsonian meaning of affordance to cover nonprojectable features, that is, learned aspects of interaction. For example, the fact that a chair is a museum piece may not change the Gibsonian affordance that one may sit in it; however, learning has endowed this situation with additional information, retrieved from memory, that prevents sitting.) For an adult human, a kitchen chair affords sitting, standing on, or even lifting to flick a snake off a porch with one of the chair's legs. For a toddler, the chair affords sitting and standing on, as well as hiding under in a game of hide and seek. The chair does not afford lifting for the toddler, however, because the toddler is not strong enough to lift it. Because the affordances of the chair differ for the adult and the child, the claim is that the meaning of the chair also differs. *Mesh* refers to the process by which affordances are combined to accomplish goals. The mesh process must respect both body and physics. Thus, an adult can mesh the affordances of a kitchen chair (e.g., it can be lifted to expose a leg) and the affordances of a porch (e.g., it affords secure footing) to accomplish the goal of flicking a snake off the porch. It is hard to imagine, however, how the adult could mesh the affordances of a beanbag chair to accomplish the same goal; hence beanbag chairs have a different meaning.

This action-based account of meaning seems to be far from our everyday sense of meaning, that is, the sort of meaning conveyed by language. In fact, however, the data (to be reviewed shortly) point to a strong connection, and the *indexical hypothesis* (IH) was developed by Glenberg and Robertson (1999, 2000) to provide a theoretical description of that connection. The IH postulates that three, temporally overlapping processes—(a) indexing, (b) derivation of affordances, and (c) meshing as directed by grammar—are used to convert words and sentences into embodied, action-based meaning. That is, we go from the words to a consideration of the actions implied by the sentence; if we can create a smooth and coherent (i.e., doable) simulation, then we can understand the sentence.

Consider how a person might understand a sentence such as "Art flicked the snake out of the way using the chair." The indexing process maps words (e.g., "Art") and phrases (e.g., "the chair") to objects in the environment or to perceptual symbols (Barsalou, 1999). Perceptual symbols are neurally based representations of objects and events that are extracted from perceptual stimulation by selective attention. Thus, on seeing a kitchen chair being used as step stool, one might attend to its height, the fact that it has a flat seat, and that the back is situated to afford grasping and balancing while standing on the seat. These aspects of the representation maintain their neural basis in that they are stored in areas of cortex associated with the initial perceptions. Thus, the information regarding the flat seat is stored in visual areas, whereas the ability to grasp the back is stored in motor areas (see discussion by Hauk, Johnsrude, & Pulvermüller, 2004). Later, if the chair has just been varnished, the smell of the chair will be stored in olfactory areas and linked together with the other aspects of the chair representation. With sufficient experience, these representations take on the properties of simulators (Barsalou, 1999); that is, the analogically encoded properties of a chair can be cognitively combined with other representations, such as that of standing or hefting or hiding. So, according to the first process of the IH, on reading the sentence, one probably indexes "Art" to the perceptual symbol of a male human and "the chair" to the perceptual symbol of, perhaps, a kitchen chair.

According to the IH, affordances are derived from the objects (or their perceptual symbols), not the words. Note that words do not have affordances in the usual sense; that is, people do not interact with words as they do physical objects. Instead, it is the objects that words designate that have affordances and are a major source of meaning As noted by Barsalou (1999) and Pulvermüller (in press), word forms (e.g., the sound of the word *chair* or the way the printed word looks) have perceptual characteristics stored in auditory and visual areas of the brain, but affordances come from associating those word forms with perceptual experiences of the referents. (See Glenberg & Robertson, 2000, and Kaschak & Glenberg, 2000, for demonstrations that understanding both familiar and unfamiliar concepts depends on accessing perceptual information, not just putative abstract concepts.)

The third, temporally overlapping process specified by the IH is that grammatical knowledge of several sorts is used to mesh or combine the affordances into a coherent simulation. For example, the syntax of "Art flicked the snake out of the way using the chair" indicates that Art did the flicking, not the snake. In addition, knowledge of the meaning of the syntactic construction sets the goal for the mesh process, that is, what the meshing must accomplish. For example, the first part of the sentence (up to *using*) is in the form of the caused motion verb-argument construction (Goldberg, 1995). Goldberg (1995) proposed that this syntactic construction (subject–verb–object–locational phrase) conveys the meaning that the subject ("Art") causes the motion of the object "the snake" to a location ("out of the way"). Kaschak and Glenberg (2000) demonstrated that English speakers are sensitive to these sorts of constructional meanings and that speakers use the meaning of the constructions to help determine the meaning of the individual words within the construction. Other sorts of grammatical knowledge (e.g., the meaning of temporal adverbs such as *while* and *after*) direct the temporal course of the meshing process (De Vega, Robertson, Glenberg, Kaschak, & Rinck, 2004).

The IH proposes that a sentence is understood to the extent that the meshing process results in a coherent, that is, doable, simulation of action. Consider what would happen, however, if you happen to index "chair" to your favorite beanbag chair. Beanbag chairs do not afford (easy) lifting, let alone the flicking away of snakes. In this case, you might consider the sentence to be nonsense or the speaker to be misinformed. The point is that the same words in the same sentence might be deemed perfectly sensible or nonsense depending on how those words are indexed, the affordances derived, and whether those affordances can be meshed as directed by syntax.

A tremendous amount of evidence is accumulating that supports the notion that linguistic meaning is based on the body's perception and action systems, that is, the systems that derive and mesh affordances. For example, Hauk et al. (2004) recorded brain activation while participants listened to verbs such as *pick*, *kick*, and *lick*. While listening to *pick*, the brain was especially active in that portion of the motor strip that controls finger movements, whereas when listening to *kick*, the activation was greatest in the portion of the motor strip controlling the leg. As another example, Borghi, Glenberg, and Kaschak (2004) had participants read sentences such as "There is a car in front of you" and then verify whether probe words (e.g., *roof*, *wheel*, or *road*) named a part of the object mentioned in the sentence (e.g., *car*). In one condition, participants responded "yes" by moving the arm upward to reach a response button labeled *yes*, and they moved downward to reach a button labeled *no*. In the other condition, people responded "yes" by moving to the lower button and "no" by moving to the upper button. What would be expected if the mere reading of a word such as *roof* activated action-based meaning? Because the roof of a car is near the car's top, interacting with a roof requires movement upward, and the mere reading of the word should prepare one to act in an upward manner. Consistent with this prediction, people responded faster to words such as *roof* when the yes response required an upward movement than when it required a downward movement. Just the opposite was found for words like *wheel*. A more complete review of these data can be found in Glenberg (in press).

ACTION AND ABSTRACTION

The IH might work for concrete objects and actions such as "wheel" and "kick"; however, any theory of language and conceptualization must also be able to account for what appear to be abstract ideas such as "p or not-p," "truth," and grammatical knowledge. Furthermore, such a theory must account for how differently abled people (e.g., people with disabilities) can understand. A complete discussion of these issues would be well beyond the mandate of this chapter, but it may be useful at least to sketch some possibilities. Lakoff (1987) discussed how logical predicates, such as "p or not-p," might be understood. He began by noting that some types of human activities, such as dealing with containers, are virtually universal. From activities such as filling containers, drinking from them, putting the hand inside and outside, and so on, we develop, in Lakoff's terminology, image schemas, which are similar to Baraslou's (1999) simulators. It is important to note that the activity of interacting with containers is structured by how the body works. For example, a finger can be inside the container, or outside the container, but rarely both. Thus, the understanding of a container becomes structured with the equivalent of "things can be inside or outside, but not both." According to Lakoff, logical rules such as "p or not-p" are understood by analogy to concrete experiences with the right structure, such as the container simulator. (For another example, see Barsalou's discussion of how concepts such as "truth" and "or" can be built from perceptual symbols.)

Glenberg and Kaschak (2002; see also Glenberg & Gallese, 2006) discussed how grammatical knowledge can be built from action. Consider our understanding that the grammatical form S-V-O-O implies transfer. Thus, "Art gave Danielle the book," "Art sent Danielle the book," and even "Art blicked Danielle the book" all seem to indicate that Danielle got the book from Art by different means, even if we are uncertain what those means may be. Tomasello (2000, 2003) has documented how children first acquiring their native language learn verb islands such as "give me X." These islands coalesce around frequent exemplars of verbs, such as *give*, and only with extensive experience do children develop the full adult S-V-O-O construction (Casenhiser & Goldberg, 2005). Now, imagine a baby who is first learning the meaning of *give* by having an adult say "Give me the cup." While making the utterance, the adult may literally stretch the baby's arm and open the baby's hand. The actions of stretching out and opening the hand then become the meaning of "give X." As the baby hears more language and can use that language to direct attention to several objects in the environment, the baby can learn to understand more complex forms, such as "Give Momma the cup"; that is, *give* initiates an arm action that will end with a hand opening to release whatever is in the hand (e.g., a cup). On hearing the word *Momma*, the baby's attention is directed toward the mother, and the affordances of the mother are perceived. Some of those affordances are related to the fact that Momma can also grasp the cup (that she is an appropriate recipient) and that she is in a particular location. We suppose that the child learns to use the location of Momma to guide the arm action corresponding to giving. Thus, the grammatical structure of the construction corresponds to the structure used to control action associated with transfer (Glenberg & Gallese, 2006).

The action-based understanding of the abstract concept of transfer is exactly what is implied by experimental data. Glenberg and Kaschak (2002) found that requiring an arm movement in opposition to arm extension interferes with understanding sentences such as "Give Danielle the book." Furthermore, such an arm movement also interferes with the understanding of sentences such as "Tell Danielle the secret"; that is, the abstract notion of transfer of information is grounded in the simple action of transfer of objects. In fact, this same sort of mechanism appears to be operating in the understanding of counterfactuals such as "If she had been more discreet, Art would have told Danielle the secret," as demonstrated by De Vega (in press).

Within an action-based account of language and cognition, there are good reasons to suspect that differently abled people will develop concepts similar to others; that is, a differently abled person will have perception and action systems substantially similar to the population norm and hence will interact with the world in substantially similar ways. Thus, a congenitally blind person will be able to understand "p or not-p" much as a sighted person because the blind person interacts with containers in a similar manner. Nonetheless, the account predicts specific, albeit subtle, deficits that are beginning to be found. For example, Neininger and Pulvermüller (2003) investigated language understanding in patients with lesions in areas controlling action or vision. The patients did not report any language difficulties, and there were few deficits on standard neuropsychological assessments (and no indication of aphasia). Nonetheless, with the speed stress of a lexical decision task, the patients with lesions in areas controlling action made more errors on action words than did patients with lesions in visual areas, and the reverse was found for errors on words referring to visual properties. Thus, differences in perceptual and action systems do influence language understanding, although for two reasons, apparently large differences in abilities (e.g., the blind person or the person with paraplegia) need not have correspondingly large differences in understanding. First, when one system functions differently, there will be substantial overlap among people in the great variety of other perceptual and action systems, thus constraining how situations and language can be understood. Second, patients often have ample opportunity after trauma to develop alternative routes for understanding (e.g., after damage to visual areas, the patient might use proprioception to recover spatial information that might otherwise be based on vision.)

ACTION AND LEARNING TO READ

Why are some children verbally skilled when it comes to conversation, but hate to read? For some children, the problem may be poor fluency due to inadequate practice (e.g., Rayner, Foorman, Perfetti, Pesetsky, & Seidenberg, 2001), or failure to develop powerful reading strategies as described in many of the chapters in this volume. We suspect, however, that part of the problem is related to indexing. Consider the situation when a child is first exposed to language as a baby. Almost all of the words are immediately indexed to objects and actions (Masur, 1997). For example, when a mother says, “Here is your bottle,” she is actually holding the bottle and directing the child’s attention to the object and the actions associated with that object. Or, when a father says, “Wave bye-bye,” he demonstrates how to wave. The point is that when learning an oral language, indexing is frequent and immediate, reinforcing the connection between words and the objects or their perceptual symbols. Consider now the situation when a child is learning to read. By necessity, the child must focus on the arduous process of decoding, that is, producing sounds from the letters. Thus, the child’s attention is explicitly drawn away from the to-be-indexed objects to the letters of the word. Furthermore, the relevant objects are unlikely to be present in the environment, and there is certainly none of the gesture found in conversation. Even if a child is successful in pronouncing the word by combining the sounds of letters (e.g., “duh awh guh”), the blending of the sounds and their prosody is much different from the smooth production found in conversation (e.g., “dog”). Because of the differences in the sound of spoken words compared to

Breakfast on the farm

Ben needs to feed the animals.
He pushes the hay down the hole. 🚦
The goat eats the 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 9.1. Top: Example of a story from the farm scenario with "green light" signals. Bottom: The farm scenario toys.

sounded-out words, the latter is an unreliable cue to the perceptual symbol of the object. In short, we suspect that some children find reading to be an unrewarding activity because they have not learned to successfully index the written word. For those children, reading is an effortful and boring exercise in word calling.

Glenberg, Gutierrez, Levin, Japuntich, and Kaschak (2004) developed an early-reading intervention designed to ensure indexing of written words to objects. First- and second-grade children read short stories about scenarios,

TABLE 9.1
Effects of Physical and Imagined Manipulation

Type of manipulation	*Day 1 (story1) physical*	*Day 1 (story2) imagine*	*Day 2 imagine*	*Day 3 no instruction*
Group	**Proportion recall of action sentences**			
Manipulate	.62	.66	.63	.70
Re-read	.29	.31	.24	.47
	Proportion correct on spatial inference questions			
Manipulate	.93	.83	.89	.86
Re-read	.76	.72	.64	.75

such as stories about life on a farm. In front of the child was a set of toys (see Figure 9.1) to which the words could be indexed. In the *physical manipulate* condition, children read aloud critical sentences (those signaled by a picture of a green traffic light) and then were taught to move the toys to correspond to the sentences. This procedure virtually guarantees that the child indexes the words to objects and meshes the affordances in order to correctly move the toys. In the *reread* condition, children also read about the scenario, and the toys were in front of them. However, when these children saw a green light, they were to reread the sentence. After reading and a 2-minute interval filled with distracting conversation, the children were asked to recall as much of the story as possible, and they were asked a series of inference questions that required integration of text and scenario knowledge.

As shown in the first column of Table 9.1, the children who used physical manipulation recalled more, and more successfully answered the inference questions, than children who read and reread the critical sentences. The effect size (Cohen's *d*) for recall was 1.39, and for answering the inference question it was 0.81. In other words, the effects were substantial.

After applying physical manipulation, the children were taught to imagine manipulating the objects; that is, they were told to figure out how they would move the objects, but instead of actually moving them, they were to imagine moving them. In the reread condition, the children were taught to read the text once out loud and once silently. Columns 2 and 3 in Table 9.1 show that the benefits of manipulation extend to imagined manipulation. That is, children do not have to always physically manipulate; once they learn how to index, the indexing can be done in imagination, much the way we suppose that competent adults read. The effect sizes for imagined manipulation compared to reread were 1.87 and 1.50 for the recall and question answering, respectively. On the third day of the experiment, children were asked to read texts (that had the green lights), but they were not prompted to use any particular strategy. The finding (fourth column in Table 9.1) that children who had previously used physical manipulation and imagined manipulation were still comprehending and remembering more than children who had reread demonstrates that the imagined manipulation strategy is readily maintained (d = 1.23 for recall).

The results from two other experiments further demonstrate the efficacy of the manipulation technique. Glenberg, Brown, and Levin (in press) had children participate in groups of three. One child would read a sentence and manipulate the toys while the others watched, then the next child would read and manipulate, and so on. The results indicated that the benefits of manipulation compared to rereading extended to watching other children manipulate (d = 1.72). Marley, Levin, and Glenberg (2005) used the manipulation technique with Native American children with learning disabilities. The children listened to the story and then observed the outcome of the experimenter manipulating, or thought about each sentence as it was presented. Much as in Glenberg et al.'s (in press) experiment, memory for the texts was enhanced by observing the outcome of manipulation (effect sizes varied from 1.23 to 1.75 for different measures).

Richmond and Glenberg (2006) investigated an application of physical manipulation and imagined manipulation to the learning of an abstract principle in science, the *control of variables strategy* (e.g., Triona & Klahr, 2003). The principle of the control-of-variables strategy is that when designing an experiment, all variables other than the focal independent variable should be controlled, or held constant. In research with fourth-grade students, we are investigating whether initial physical manipulation helps the children implement an imagined manipulation strategy when later asked to learn from text. In the experiment, children have available the apparatus for setting up experiments to investigate questions such as whether the shape of an object affects the speed with which it sinks in a cylinder of water. In one condition, children read instructions and literally set up an experiment by controlling some variables (e.g., the height from which an object is dropped), while manipulating another variable, such as object shape. In another condition, children read the same instructions, but the experimenter sets up the experiment out of the children's sight. Later, all children are asked to judge the adequacy of other experiments from text alone. Whereas initial results are encouraging, we do not yet have enough data to draw definitive conclusions.

In summary, the point of reading is to convey meaning. But what is meaning? According to the IH, meaning arises from creating or simulating the perceptual/action situation described by sentences. These simulations are determined by the properties of the objects referred to, that is, the affordances of the objects, not the properties of the words. Physical and imagined manipulation help children to index words to objects so that affordances can be derived and meaning achieved. In chapter 12 of this volume, Johnson-Glenberg reviews other data demonstrating the importance of the application of visually based strategies for reading comprehension.

ACTION AND MATHEMATICAL STORY PROBLEM SOLVING

A good deal of evidence indicates that story problems are particularly difficult for children (e.g., Cooney & Swanson, 1990; Fuchs & Fuchs, 2002; Light & DeFries, 1995; Robinson, Menchetti, & Torgesen, 2002). We speculated that one reason for this difficulty is that some of the children were not adequately understanding the story, rather than their having some particular difficulty with math. If physical manipulation and imagined manipulation improve story understanding, will they also improve performance on story problems?

We created six types of problems set in two scenarios: (a) a fair (with rides, tokens, two children, a clown, and balloons) and (b) a zoo (with various animals, food for the animals, and a zookeeper). The problem types ranged from relatively simple addition problems to those requiring a combination of addition and multiplication (or repeated addition), to division. Figure 9.2 contains one of the problems calling for a combination of multiplication and addition. We refer to these as *Each problems* because of the importance of the word *each*; that is, in these problems, the word *each* signals that there are multiple alligators and multiple hippos and that each of the several individuals must be fed.

Children in the third grade were randomly assigned to one of three conditions. In the *story-relevant manipulation condition*, children manipulated the characters and objects much as in Glenberg et al.'s (2004) experiments. For example, in dealing with the Each problem illustrated in Figure 9.2, children would count out the appropriate number of little toy fish and distribute them to the animals. The *abstract manipulation* group was designed to simulate a type of manipulation that occurs in classrooms, such as the use of counting sticks to help solve problems. Note that these manipulables are often unrelated to the plot content of the story problem. Thus, children in the abstract-manipulation condition counted out Lego pieces whenever there was a green light sentence. These pieces were not shaped like the objects in the stories (e.g., fish or balloons); neither were the story objects present. On the other hand, the abstract manipulation condition does control for physical activity and any benefits of counting out objects. Children in the *reread* group read each sentence aloud and immediately reread those sentences with green lights. All children were told that the green light sentences contained particularly

Feeding the Hippos and the Alligators

There are 2 hippos and 2 alligators at the zoo.

They live by each other, so Pete the zookeeper feeds them at the same time.

It is time for Pete to feed the hippos and the alligators.

Pete gives each hippo 7 fish.

Then he gives each alligator 4 fish.

The hippos and alligators are happy now that they can eat.

How many fish do both the hippos and the alligators have altogether before they eat any?

Figure 9.2. **T**op: Example of an Each problem from the zoo scenario. Bottom: The zoo scenario toys.

important information. After reading the problems, children wrote an answer and a number sentence (or equation), indicating how they solved the problem. Because these two measures produced essentially identical findings, we focus on the answers measure.

Children participated in three sessions. On the first day, they solved problems related to one of the scenarios, and on the second day they solved problems related to the other scenario. On the third day, children in the story-relevant manipulation condition were taught imagined manipulation, children in the abstract-manipulation condition were asked to imagine counting out the Lego pieces, and children in the reread condition were asked to reread green light sentences silently. All children worked on problems from both scenarios during this third session.

The initial analyses of the results were quite disappointing in that there were no statistically significant differences among the story-relevant manipulation, abstract-manipulation, and reread groups. On closer inspection, however, we found an intriguing effect dependent on problem type. Some problems appeared to be too easy and resulted in close to ceiling effects; other problems (e.g., the division problem) were too difficult for most of the children. However, the data from the Each problems were just right: Collapsing across the first two days, the percentages correct were 75%, 28%, and 35% in the story-relevant manipulation, abstract-manipulation, and reread conditions, respectively (d = 1.09 for the contrast of story-relevant manipulation to abstract manipulation). The story-relevant manipulation advantage was also found on Day 3, when imagined manipulation was used: 50%, 40%, and 13% for the story-relevant manipulation, abstract-manipulation, and reread conditions, respectively. However, the differences on Day 3 were not statistically significant—perhaps because of low statistical power in that, on average, there were fewer than one Each problem per child on Day 3.

The second experiment was designed to follow up on these findings in several ways. First, given that the effect with Each problems was not predicted, we needed to replicate that finding. Second, there were only two Each problems (one for each of the scenarios), so the finding might have been due to idiosyncrasies with those two problems. In the second math experiment, there were six Each-type problems for each of the scenarios. Third, each child solved two Each-type problems on Day 3 using an imagined-manipulation strategy. The sessions were all exactly 1 week apart, so finding an effect of condition on Day 3 would indicate an effect of physical manipulation lasting at least 1 week.

Fourth, we tested a hypothesis as to why story-relevant manipulation would be particularly effective for Each problems but not others. Suppose that these third-grade children are not particularly skilled in understanding some grammatical constructions, such as the word *each*. Note that the correct understanding of *each* is quite complicated: The word must be indexed to the correct set of objects, and the objects within the set need to be individuated. For example, it is not sufficient when reading *each* for the reader to note that there is a group of alligators. In addition, the child must realize that there are two alligators and that both are fed individually. The story-relevant manipulation condition makes this individuation relatively obvious, however, because the child has to count out fish for each of the alligators (or, in the Fair scenario, count out tickets for each of the rides). In fact, the most frequent error in both the abstract-manipulation and reread groups was to count out only once, as if the child failed to individuate the animals in a group. For example, for the problem in Figure 9.2, the

TABLE 9.2
Proportion Correct Answers from the Second Math Experiment

	Sessions 1 and 2 (Physical Manipulation)		
Condition	*Each*	*Each Plural*	*Each Enumerated*
Story-Relevant Manipulation	.78	.72	.72
Abstract Manipulation	.5	.61	.67
Re-read	.33	.27	.4
	Session 3 (Imagined Manipulation)		
Condition	*Each*		*Each Enumerated*
Story-Relevant Manipulation	.76		.76
Abstract Manipulation	.38		.62
Re-read	.40		.47

most frequent answer in the abstract-manipulation and reread conditions was 11, rather than the correct answer of 22.

To test the individuation explanation, we manipulated the degree of linguistic support for the correct interpretation of *each*. In Each Plural problems, the wording of the green light sentences was changed from, for example, “Pete gives each hippo 7 fish” to “Pete gives each of the hippos 7 fish.” That is, the noun was explicitly marked as plural. In Each Enumerated problems, the wording was changed to “Pete gives each of the 2 hippos 7 fish.” That is, the noun was marked as plural and the actual number (2) was given. We reasoned that providing more linguistic support, so that children in the abstract-manipulation and reread conditions did not have to depend solely on their ability to index the word each, should improve performance and reduce the difference between these groups and the story-relevant manipulation group.

The data from the second experiment are presented in Table 9.2. Note that we successfully replicated the effect from the first experiment; namely, for Each problems, children in the story-relevant manipulation condition were far more successful than children in the abstract manipulation (d = 0.80) and reread conditions (d = 1.5). Also, the effect was maintained on the third, imagined manipulation, day; that is, children who had previously used physical manipulation solved problems more accurately when using imagination than children in the other conditions (d = 0.73).

Nonetheless, there was only modest support for the hypothesis that Each problems are difficult because children do not use the word *each* to index a group composed of individuals. First, the effect of problem type (Each, Each Plural, or Each Enumerated) was not statistically significant; neither was the interaction with condition statistically significant. Second, whereas there is a hint that adding linguistic support helped the children in the abstract-manipulation

TABLE 9.3
Problem Type 1 From the First Math Experiment Feeding the Monkey and the Polar Bear

Pete the zookeeper is in charge of feeding animals at the zoo.
In the morning Pete feeds the polar bear and the monkey.
First he feeds the polar bear 9 fish.*
Then he feeds the monkey 5 bananas.*
In the afternoon he feeds the polar bear 8 fish.*
Now, Pete remembers he has to feed the monkey again.
If the monkey gets the same number of things as the polar bear, how many bananas should Pete give the monkey in the afternoon?

*Sentences followed by green lights.

group, linguistic support had mixed effects in the story-relevant manipulation and reread groups. In summary, although we have demonstrated some very large effects of manipulation and imagined manipulation in story problem solving, the boundary conditions for the effect are not yet clear.

We are currently investigating two new hypotheses in addition to the individuation hypothesis. The first new hypothesis is that, when faced with story problems, many children will ignore the story plot. When the plot provides information useful for problem solving (as in Each problems), these children will suffer. Because story-relevant manipulation forces the child to pay attention to the plot, children in the story-relevant manipulation condition outperform other children when the plot conveys important information.

A second new hypothesis addresses the congruence between the mathematical structure of the problem and the structure revealed by manipulation. For Each problems, the actions used in story-relevant manipulation mimic the structure of the mathematics; that is, the child counts out each number twice corresponding to the multiplication or multiple additions required to solve the problem. In contrast, consider the problem in Table 9.3. For this sort of problem, the counting out reveals some of the mathematical structure, but important steps are missing. That is, after counting out 9, 8, and 5, the solution requires the summing of 9 and 8 and then subtracting 5. The simple story-relevant manipulations do not mimic these latter steps. In fact, for two reasons, the story-relevant manipulation children might do poorly on the type of problem illustrated in Table 9.3. First, the manipulations leave the child hanging, because they do not specify the final steps. Second, it may be difficult for the child to conceptualize how to subtract 5 bananas from 17 fish! In fact, in the initial math experiment, story-relevant manipulation children were correct on only 46% of these problems, whereas children in the other conditions were correct on 60% of these problems. A similar analysis can hold for the division problems used in Experiment 1; that is, a simple counting-out strategy does not reveal much of the structure that corresponds to division (e.g., dividing the tokens into equal-sized piles). This hypothesis suggests that manipulation more sophisticated than simply counting out tokens may be more broadly applicable. For example, manipulation that emphasizes one-to-one correspondence might help children to solve problems such as those in Table 9.3, in which children must consider the equivalence between the number of fish and the number of bananas. Similarly, teaching manipulation in which equal-sized piles are created might help children to ground the concept of division. Nonetheless, these speculations remain to be tested.

IS MANIPULATION PRACTICAL FOR THE CLASSROOM?

Three aspects of our results suggest that manipulation may work well in the classroom. The first result is evidence for strategy maintenance and transfer. As described earlier, Glenberg et al. (2004) found that children who had brief training in physical manipulation followed by imagined manipulation maintained the strategies without further instruction several days after the last instructed session. A type of maintenance was also found in the second math experiment. Namely, the third session (in which imagined manipulation was taught) was a week after the last physical manipulation session. Nonetheless, the children were able to use memory of their physical experiences to enhance problem-solving performance compared with children who only read the problems. Finally, data from a third math experiment (Glenberg, Rischall, & Jaworski, in preparation) demonstrate both maintenance and transfer. That experiment was similar to the second math experiment reported here, except that 1 to 3 weeks after Session 3, the children were tested again in their classrooms with no scenario toys present. This test consisted of two Each-type problems, one from a scenario with which the child was familiar and one from a different scenario. For the familiar scenario, children who had had story-relevant manipulation (physical manipulation followed by imagined manipulation) solved 69% of the problems, whereas children who had reread solved only 46% ($d = 0.46$). For the unfamiliar scenario, the children never saw the corresponding toys; neither were they given any introduction to the scenario. Nonetheless, the children who had practiced story-relevant Manipulation earlier solved 46% of the problems compared to the reread children, who solved only 23% ($d = 0.48$). Thus, after fairly minimal training, the strategy is maintained for at least 3 weeks, and it transferred to a new scenario in a new environment.

A second reason for expecting success in the classroom comes from data demonstrating the effectiveness of group strategy training with children from diverse backgrounds. In Glenberg et al.'s (in press) study, low-income children attending after-school programs in community centers were given physical manipulation or reread training in groups of three. As noted earlier, the physical manipulation strategy was quite effective in this situation. Also, as Marley et al. (2005) reported, Native American children with learning disabilities benefited from listening combined with seeing the results of the experimenter's manipulations.

A third reason for optimism stems from the success of manipulation techniques in schools. As Lillard (2005) described, many of the successful methods used in Montessori schools take advantage of physical manipulation. In fact, Maria Montessori wrote:

> One of the greatest mistakes of our day is to think of movement by itself, as something apart from the higher functions … Mental development must be connected with movement and be dependent on it. It is vital that educational theory and practice should become informed by this idea. … 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. (Montessori, 1967, pp. 141–142)

Thus, Montessori agrees: Brains are for action!

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