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How reading comprehension is embodied and why that matters

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Abstract

Reading comprehension, much like comprehension of situations and comprehension of oral language, is embodied. In all cases, comprehension is the ability to take effective action on the basis of affordances related to the body, the physical world, and personal goals and cultural norms. In language contexts, action-based comprehension arises from simulating the linguistic content using neural and bodily systems of perception, action, and emotion. Within this framework, a new approach to teaching reading comprehension is described: Teach children how to simulate while reading. The *Moved by Reading* intervention teaches simulation in two stages. In the first stage, physical manipulation, children manipulate toys to simulate the content of what they are reading. After success in physically manipulating the toys, the children are taught to manipulate the toys in imagination. Research demonstrates that both physical and imagined manipulation leads to large gains in memory and comprehension.

Keywords: Reading comprehension, embodiment, Moved by Reading

Introduction

What does it mean to comprehend? Does comprehension differ when understanding situations, oral language, or written texts? Does the nature of comprehension hold any implications for the nature of instruction? These are some of the questions I hope to answer in this essay. In brief, I will propose that comprehension is related to action: Understanding a situation or a text means that the understanding can be used to guide effective action, and that this definition holds whether one is understanding situations, dialogue, or text. Furthermore, because understanding guides literal action, understanding is closely related to bodily abilities. Finally, understanding the embodied nature of reading comprehension suggests an effective technique for teaching reading comprehension skill to even the

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youngest of readers. This technique, called *Moved by Reading*, works by having children physically and cognitively interact with text so that an embodied, action-based understanding of the text is achieved.

Understanding situations and language

Let's begin with a commonsense approach to understanding. When walking down the street, sitting at work, or talking with friends at a ballgame, what might it mean to understand? Understanding is not just a cognitive state. If one were to stop moving and simply think about the situation at hand, others would certainly become alarmed. "Hey buddy! You can't just stand there in the middle of the street!" But it is also the case that in any particular situation, most actions are inappropriate: While at work or school you can't start to dance, shout out loud, pretend to swim, or intensively groom yourself or others. If you did, it would certainly be appropriate for someone to say, "Don't you understand where you are?" Thus, understanding a situation is, at the very least, *revealed* through appropriate action, that is, action that is constrained by the physical situation, bodily capabilities, social and cultural norms, and particular goals. However, I will argue further that the ability to act appropriately does not just reveal understanding but constitutes understanding.

A similar sort of commonsense analysis holds for understanding oral language, as in a dialog. If I say, "Wow, the other day Art freaked out at work: He was trying to swim down the hallway," and you respond with "I really don't like to travel on airplanes," I would be justified to ask, "Hey, did you understand what I said?" Again, understanding is revealed by appropriate action in the situation, here a conversation. Yet, there seems to be a big difference between action that involves large body movements, such as pretending to swim, and action that consists of moving the speech articulators to make noises.

The difference between large body movements and speech is resolved with the concept of simulation (Barsalou, 1999; Barsalou, 2008; Gallese & Lakoff, 2005; Glenberg & Gallese, 2011; Zwaan & Taylor, 2006). According to the simulation theory of language comprehension, language is understood by simulating the situation described by the language, that is, by driving the brain into states that are analogous to the perceptual, action, and emotional states that arise during perception of and acting in the real situation. Thus, understanding, "He was trying to swim down the hallway," utilizes a) visual perceptual systems that are active in seeing a real hallway and seeing real motion, b) motor systems that would be used in swimming, and c) emotional systems that would respond to the odd, upsetting, and perhaps frightening situation of seeing a grown man acting inappropriately.

There is a large and growing literature supporting the claims of simulation theory (for reviews see Glenberg, 2007; Kiefer & Pulvermüller, 2011; Fischer & Zwaan, 2008). Here I will describe just a smattering of that evidence. If simulation theory is correct, then upon hearing verbs such as lick, pick, and kick, there should be somatotopic activation of the motor system that controls the mouth, the hands, and the legs, respectively. That is exactly what was reported by Hauk, Johnsrude, & Pulvermüller (2004) who measured brain activity using functional magnetic resonance imaging (fMRI) while people listened to verbs. Similarly, when reading sentences describing transfer of objects from one person to another, simulation theory predicts greater activity in the neural and muscular systems controlling the hand than when reading about the same objects and people without any mention of action. This differential neural-muscular activity was demonstrated using single-pulse transcranial magnetic stimulation (Glenberg et al., 2008).

There is also evidence supporting the claim from simulation theory that perceptual mechanisms are engaged during language comprehension. For example, when people understand sentences that describe motion, there is greater activity in areas V5/MT (that specializes in the visual perception of motion) than when understanding sentences that describe a visual scene without motion (Rueschemeyer, Glenberg, Kaschak, Mueller, & Friederici, 2010).

Finally, simulation predicts that understanding of language with emotional content involves neural and bodily systems of emotion. Havas, Glenberg, Gutowski, Lucarelli, & Davidson (2010) asked people to read sentences describing happy, sad, and angry events. As predicted by simulation theory, while reading about happy events, there was greater activity in the muscles that control smiling, and when reading about sad and angry events, there was greater activity in the corrugator muscle used in furling the brow. Simulation theory also predicts that if the ability to engage in a simulation is blocked or reduced, then comprehension should suffer. Havas et al. (2010) produced evidence consistent with this prediction using a rather unusual procedure involving cosmetic Botox. Cosmetic Botox injections in the corrugator muscle blocks activity in the muscle and reduces frown lines. According to simulation theory, not being able to frown should increase the difficulty of simulating sadness and anger. Remarkably, that is just what was found: Reading of sad and angry sentences was slowed after Botox injections in the corrugator muscle, but reading of happy sentences was unaffected.

One objection to simulation theory is that much of human knowledge is abstract, and hence cannot be captured by bodily systems of perception, action, and emotion. However, this objection is incorrect in at least four ways. First, there are data demonstrating that at least some abstract ideas are closely related to bodily systems. For example, Glenberg et al. (2008) demonstrated that understanding of sentences describing the transfer of abstract information (e.g., "Anna delegates the responsibilities to you") activates the motor system to the same extent as the understanding of sentences describing the transfer of concrete objects (see Santana & de Vega, 2011, for additional examples). As another example, Kousta, Vigliocco, Vinson, Andrews, & Del Campo (2010) have shown that many abstract ideas have a significant grounding in the emotional system.

Second, Barsalou (1999) has proposed that some abstract ideas can be understood as embodied relations or processes. Consider, for example, truth. The notion of truth often requires a comparison between a situation and a description of the situation. Thus, to ask, "Is it true that it is raining outside?" requires a comparison between the perception of the weather outside with a simulation of the sentence, "It is raining outside." To the extent that the perceptual reality matches the simulation, the sentence is true.

Third, Lakoff (e.g., Lakoff, 1987) has adduced a tremendous amount of linguistic evidence that people think (and talk about) abstract ideas through a process of metaphorical extension. For example, most of us do not have a refined idea of what a theory is. Instead, we think about it as a physical structure. Because of that, we say things such as "The theory has a strong foundation," or "The theory is built out of thin air," and "The theory collapsed from the weight of the evidence."

Finally, there is now some speculation and data demonstrating that even the rules of syntax are not abstract in the sense of divorced from neural systems of perception, action and emotion. Instead, Glenberg & Gallese (2011) have proposed that syntax emerges from action control.

In summary, a strong case can be made for simulation theory of language comprehension. That is, we understand language by using neural and bodily systems ordinarily used for control of perception, action, and emotion to simulate the situation described by the language. Thus, we understand language much like we understand situations: in terms of the actions the situation, or described situation, affords.

Reading comprehension

The simulation account of reading comprehension is both similar to and different from the account of oral language comprehension. It is similar in two respects. First, comprehension of written text also requires a simulation of the situation described, and that simulation is based on neural systems of action, perception, and emotion. Second, for both oral language comprehension and text comprehension, the simulation arises from three processes as described by the Indexical Hypothesis (Glenberg & Robertson, 2000; Glenberg & Gallese, 2011; Kaschak & Glenberg, 2000). The first process is indexing the linguistic symbols, that is, words and phrases, to perceived objects or previous experiences. These experiences are encoded in memory as perceptual symbols (Barsalou, 1999), that is, as aspects of the perceptual, action, and emotional neural activity engendered during previous interactions with the objects. The second process is deriving affordances from the objects, that is, how it is possible to interact with the objects given the physical nature of the objects, limits of the perceiver's body, and cultural norms. The final process is meshing or integrating the affordances according to syntax. That is, the affordances are integrated so as to create a simulation of the "who does what to whom" specified by the syntax.

Nonetheless, comprehension of written and oral language differ. One difference is in how oral and written language are learned and the consequences of that learning for later performance. In learning an oral language, the indexing of symbols (spoken words and phrases) to objects is frequent and immediate. For example, a mother will say, "here is your bottle," and give the baby its bottle; or, a father will say, "Wave bye-bye" and gesture waving; or a sibling will say, "Get the ball," and point to the ball. From these interactions, the process of moving from the linguistic symbol to the indexed object or perceptual symbol is practiced, literally from day one, and becomes fast and automatic.

Relatedly, comprehension of oral language makes use of situated cues that are normally unavailable while reading. First, conversation is often about aspects of the immediate environment to which both interlocutors are attending. Thus, the objects to which words must be indexed are primed and easily accessed in the perceptual field. Second, oral language makes use of gestures (Beilock & Goldin-Meadow, 2010; Goldin-Meadow & Beilock, 2010; Hostetter & Alibali, 2008) that help to disambiguate the language and aid in indexing. Third, oral language makes use of prosody to aide in foregrounding information and conducting the correct syntactic analysis. And finally, oral language makes exquisite use of emotional information expressed in tone, prosody, facial gesture, and full-body gestures to help convey the message. For example, in talking about a sad event one may talk softly and slowly while expressing sadness on the face and with a slumped body. All of these cues to meaning are missing when reading.

Consider learning to read. Instead of frequent and immediate indexing of linguistic symbols to objects and experiences, when learning to read indexing is slow, unreliable, and rarely practiced. The beginning reader must first deal with learning the alphabet and the alphabetic principal. Then, written words can be decoded and pronounced either through a process of phonological composition or arduous memorization of individual word-forms. Even when successfully decoded and pronounced, however, the pronunciation of the written word is unlikely to be as fluent and prosodic as in speech. Thus, the word pronounced during non-fluent reading is a poor retrieval cue for meaning, that is, the non-fluent pronunciation is difficult to index to the appropriate perceptual symbol. Furthermore, when reading, the relation between the written word and object is rarely demonstrated. For example, on successfully decoding "dog," it is rare that there is a literal dog in the environment. Even when the text might have a picture of a dog, reference to the picture is haphazard. Consequently, the link between the symbol and the embodied experiences is more tenuous in the case of reading than in the case of oral language learning. Finally, many of the cues to appropriate simulation (e.g., emotional prosody) available in oral language are missing when reading. For those children who fail to make the link between the written word and the embodied experience, reading becomes a boring exercise in word-calling that rarely results in meaning.

The Moved by Reading intervention

How can a child be taught to simulate written language? Emphasizing fluency is unlikely to provide much help. Yes, to the extent that the child's pronunciations become fluent and prosodic, as in oral communication, then those pronunciations may be effective in tapping embodied experiences. However, developing this level of fluency when there is not much meaning sounds like torture. Also, it is hard to imagine how text can be read with natural prosody before meaning is easily available.

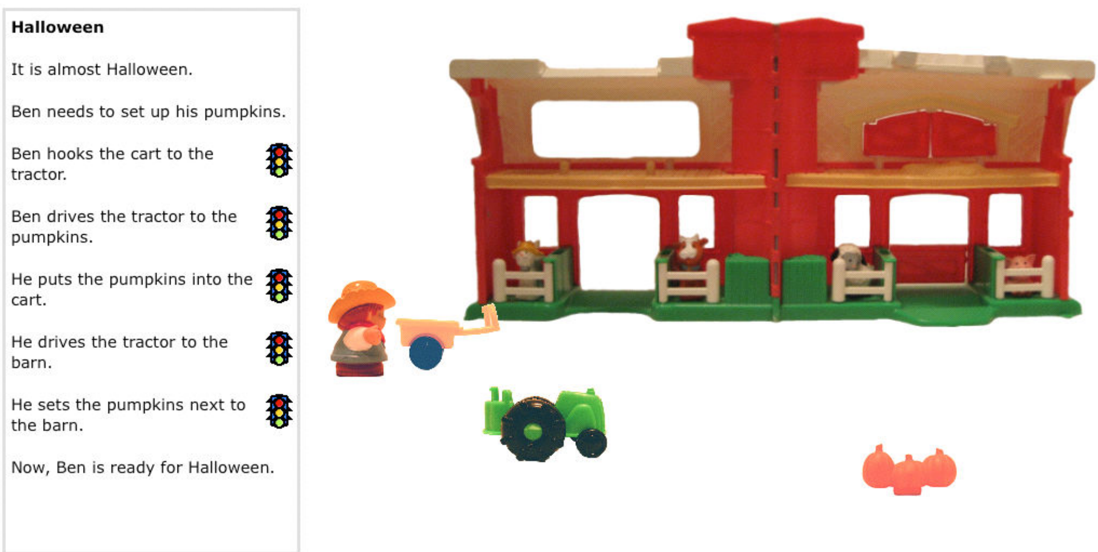
Another strategy might be to exhort the child to think about the meaning: Who has done what to whom? Why? How does this text relate to a previous text? Use your background knowledge! Create pictures/movies in your head! But, all of these exhortations presume that the child has access to meaning and is just too lazy to use it. What if the child is struggling to derive meaning from the written text?

Moved by Reading is a two-stage reading comprehension intervention designed to overcome these problems. Children read stories that relate to a particular scenario. For example, one scenario consists of stories that take place on a farm and involve animals, objects such as a tractor, and the farmer (see Figure 1). Another scenario consists of stories that take place in a house involving a mother, father, baby, and various props such as beds and a stroller. While reading these stories, the children have available either toys corresponding to the objects and characters in the scenario, or images of the toys on a computer monitor. The first stage of *Moved by Reading* is called physical manipulation (PM). During PM, children read aloud one sentence, and then move the toys or the images to simulate the content of the sentence. For example, if the sentence is "The farmer drives the tractor to the barn," then the child is to place the toy farmer into the tractor and move the tractor to the barn.

a)


Halloween
It is almost Halloween.
Ben needs to set up his pumpkins.
Ben hooks the cart to the tractor.
Ben drives the tractor to the pumpkins.
He puts the pumpkins into the cart.
He drives the tractor to the barn.
He sets the pumpkins next to the barn.
Now, Ben is ready for Halloween.

b)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c)

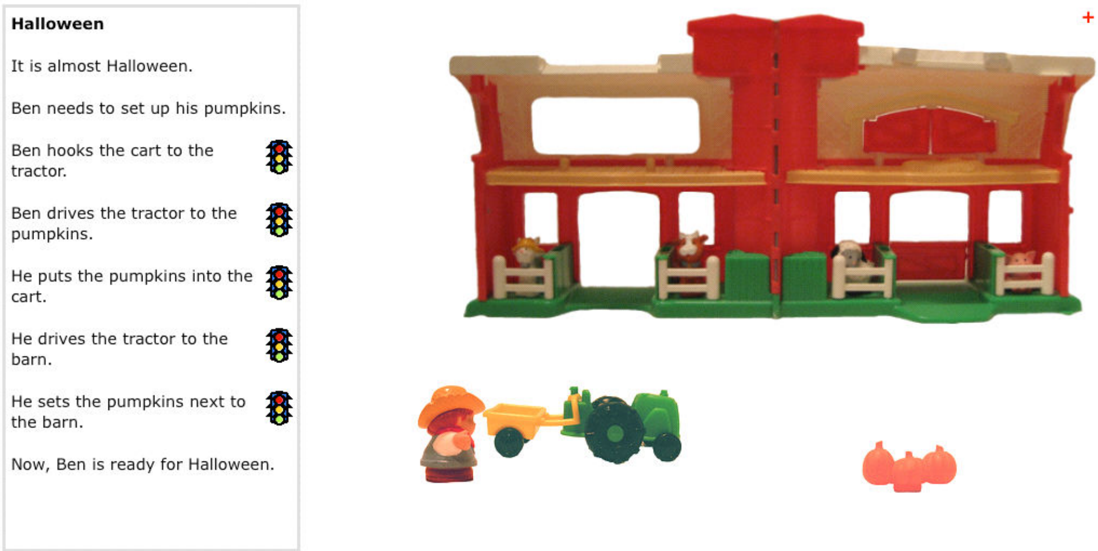

Figure 1. *(a) Screen shot before reading, "Ben hooks the cart to the tractor." (b) Screen shot midway through manipulating for "Ben hooks the cart to the tractor." (c) Screen shot after successfully manipulating for "Ben hooks the cart to the tractor." The green traffic light is the signal for the child to manipulate the toys to correspond to the sentence. Reprinted with permission from Glenberg et al. (2009)*

PM is designed to increase comprehension for the following reasons. First, the child must index the major content words to objects (or their images). This indexing can be done on a word-by-word basis, that is, it does not require understanding of the whole sentence. Because the objects are physically present, they both prime the pronunciation of the words and help to constrain the objects to which the words can be indexed. Second, the child must act out the sentence, that is, the child must physically instantiate the syntax of the sentence, the who does what to whom, in his or her own actions. The constraints of the situation (e.g., that a tractor can move easily, but a barn cannot) prime and constrain the actions that the child takes in producing the simulation. Finally, PM demonstrates for the child how written texts can be meaningful and how to uncover that meaning.

PM results in large increases in comprehension (as reviewed below), but if children always needed to physically manipulate to understand written text, it would not be very practical. Fortunately, after using PM, children can be relatively easily transferred to Imagined Manipulation (IM). The children are told to imagine moving the objects or images just as they did with PM, but now the objects and images are not physically present. Instead, the child indexes the written words to the perceptual symbols of those objects.

Visualizing or imaging content has a well-researched history in the domain of text comprehension (Bell 1986, Paivio 1986, Sadoski & Paivio, 2001). There are several important differences between earlier research and *Moved by Reading,* however. First, the instruction during IM ("imagine moving the characters like you just did") is clearer than the instruction given in many experiments investigating imagery ("create pictures in your head"). This clarity arises not from the words, but from the fact that the child has just manipulated using PM. Thus, the child can understand the IM instruction *itself* by indexing that instruction to the embodied experiences created during PM. Second, IM, in contrast to imagery instructions, is likely to engender a significant motor component in addition to visual imagery (see also, Varley, Levin, Severson, & Wolff, 1974 and Wolff & Levin, 1972). Including a motor component increases the range of information encoded. In addition, given the role of motor cortex in prediction (e.g., Bubic, Von Cramon, & Schubotz, 2010), eliciting motor activity should enhance predictive processing while reading. Thus, reading using IM enhances comprehension by encouraging indexing, by encoding multiple sources of information, and by enhancing predictive processing. When children become accomplished at IM, they become accomplished readers.

Does Moved by Reading enhance reading comprehension?

Yes, and often dramatically. Glenberg, Gutierrez, Levin, Japuntich, and Kaschak (2004) implemented an early version of *Moved by Reading* with children in the first and second grades. Working one-on-one with the experimenter, these children literally manipulated toys to simulate sentence content during PM. Performance was compared to children in a control group who read and re-read the same texts. Children in the control condition also had the toys visible, but these children did not manipulate the toys. Consider first recall of the action sentences. Children who used PM recalled 62% and children in the control condition recalled 29%, and the effect size (Cohen's *d*, the number of standard deviations between the two means) was 1.39[1]. The advantage was also found when the children were tested on their ability to correctly answer inferences based on the text, $d = .81$. Children who had used PM and were transferred to IM outperformed children in the control condition both on correct recall ($d = 1.87$) and correct inference answers ($d = 1.50$). On the third day of the experiment, the children were not given any special instructions for reading. Nonetheless, the children who had practiced PM and IM on the previous days outperformed the children in the control condition on recall ($d = 1.23$) and in answering inferences ($d = .95$, although due to a small sample size, the inference effect was not significant at the .05 level).

Recently, we implemented *Moved by Reading* as a web-based system (Glenberg, Goldberg, & Zhu, 2009; Glenberg, Willford, Gibson, Goldberg, & Zhu, 2011). When using the computer, children manipulated images on the computer screen rather than directly manipulating toys. Manipulation of the images produced benefits ($d = 1.16$) relative to re-reading comparable to those found when manipulating the toys.

Must Moved by Reading be implemented one-on-one?

Not at all. Glenberg, Brown, and Levin (2007a) implemented *Moved by Reading* with three-child reading groups. During PM, one child would read and manipulate, and then the next child would read and manipulate the next sentence, and so on. Over all, the groups that engaged in PM were much more accurate in answering comprehension questions than were children who read and reread the texts, $d = 1.72$. Interestingly, the effect was found both for questions that tapped understanding of sentences a particular child manipulated ($d = 1.26$) and for questions that tapped understanding of sentences manipulated by other children in the group ($d = 1.86$). At first glance, this result was surprising, although on reflection there are several possible explanations. First, watching another manipulate generates a vision-based memory in addition to any language-based memory. Second, watching another act will stimulate the observer's mirror neuron system (Glenberg, 2011; Rizzolatti & Craighero, 2004) and lead to neural activity in the observer's motor system that is substantially similar to the activity when the person is engaged in literal action.

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[1] Values of *d* around .2 are considered a small effect, *d* around .5 is a medium effect, and $d > .8$ is considered a large effect.

Recently, we were able to implement *Moved by Reading* for a whole classroom of students using the web-based versions of PM and IM (Glenberg et al., 2011). In this experiment, the children read to solve mathematical story problems (which will be described in more detail shortly). When measuring problem solving, children who used PM were more accurate than children who read (d = 1.19). Similarly, when those children went on to use IM while reading the story problems, they were more successful than the students who simply read the texts (d = .90).

Are there long-term benefits of Moved by Reading?

Here the data are not as secure as one would like. In Glenberg et al. (2004), there was about a week's delay between training in PM and training in IM, and another week intervened before testing with no further instruction. This final test did show a positive effect of *Moved by Reading* training, d = 1.11. For older children (third and fourth grades), Glenberg, Jaworski, Rischal, and Levin (2007b) found that minimal experience with *Moved by Reading* facilitated performance some three weeks later (d = .48). It is likely that more extensive training with *Moved by Reading* will produce larger and longer-lasting effects.

Is Moved by Reading effective for special populations?

Yes. Perhaps the most dramatic demonstration is provided by Marley, Levin, and Glenberg (2007) who investigated the listening comprehension of learning-disabled Native American children. The children were randomly assigned to three conditions. In the PM condition, the children manipulated after listening to the experimenter read a sentence; in the visual condition, the children heard the experimenter read the sentence and then watched him manipulate; in the free study condition, the children listened to the experimenter and were instructed to think about each sentence in the pause following the sentence (equivalent to the time needed to manipulate). Children in the PM and visual conditions outperformed children in the free study condition with ds > 1 for free recall of propositions, objects, and actions (but not locations), as well as cued recall. There were minor differences in favor of the PM condition relative to the visual condition (d = .32), but for the most part, these two conditions were similar. The similar performance in the PM and visual conditions probably reflects the operation of the mirror neuron system as discussed above in the context of the data from the three-person reading groups (Glenberg et al., 2007).

One way in which the data on listening comprehension differed from the usual pattern with *Moved by Reading* is that the effects observed with PM did not transfer to an IM condition. In retrospect, there are two reasons why IM was not effective in this experiment. First, the children were not given any scaffolded instruction about how to use IM [the experiments reported in (Glenberg et al., 2004) demonstrated the importance of this type of scaffolding]. Second, the children were instructed to "close your eyes and make pictures in your head." This instruction does not connect as well to PM as the standard IM instruction to "imagine manipulating the toys just as you did before."

Non-disabled Native American children were participants in research reported by Marley, Levin, and Glenberg (2010). With third-grade children, the expected *Moved by Reading* results were found. Namely, PM resulted in better free recall of stories than a reread condition, d = 1.45, and the same was true for IM (although using the instruction to "make pictures in your head"), d = 1.09. For children in the second grade, PM was effective, d = .84, but IM was not (d = .40, but the difference was not significant at the .05 criterion). These data indicate that younger children probably need more scaffolding to implement IM than do older children (see also, Marley, Szabo, Levin, & Glenberg, 2011)

Does Moved by Reading training transfer?

There are two types of transfer to consider. The first is when a child receives *Moved by Reading* training with stories from one scenario (e.g., the Farm scenario) and is asked to apply IM to stories from another scenario. In fact, the data reported above from Glenberg et al. (2007b) were collected when children were trained and tested on different scenarios. Similarly, in Glenberg et al. (2004), during the final session in which children read with no further instruction the texts were from a new scenario.

Perhaps a more interesting case of transfer was reported by Glenberg et al. (2011). The major question addressed was whether *Moved by Reading* could be considered a fundamental reading strategy, that is, one that could be used when reading in any domain. To begin to answer this question, third- and fourth-grade children were taught and practiced *Moved by Reading* while reading in narrative and expository-like domains. Then, the children were asked to solve mathematical story problems written using characters and situations from the narrative and expository-like domains. The children were not given any special instruction for how to use *Moved by Reading* in a story problem context (in contrast to Glenberg, et al., 2007b). Will helping children to understand the stories help them to solve the math problems?

Table 1. *A mathematical story problem from Glenberg et al. (2011)*

Ray enters a talent contest at school. He uses his telekinesis to perform a magic trick. It is his favorite: levitation. When objects levitate they float in the air.
Ray is among 7 contestants sitting in front of the stage waiting to perform. He is number 4. His number is called and he leaps to the stage.
There are 2 objects on the stage: a computer and a dumbbell. He surprises the audience by making the computer levitate. It weighs 22 pounds.
He hears a gasp from the audience. He then levitates the dumbbell. It weighs 55 pounds.
How many pounds in total has he lifted?
Please show all of your work.

Note: Each of the first three paragraphs ended in a green dot used as a cue to perform PM or IM (Moved by Reading condition) or an indication of important information for the Control condition.

We used two primary measures of problem-solving performance. The first was simply whether the numerical answer was correct. The second reflects a finding that Verschaffel, Van Dooren, Greer, and Mukhopadhyah (2010) describe as suspension of sense-making. That is, when some children approach story problems, they appear to give up on making sense of the story and simply try to combine numbers to do the math. To detect the suspension of sense-making, each of the stories had story-relevant numerical information that was irrelevant to solving the problem. An example is given in Table 1. In the text, the number 7 (the number of contestants) and the number 4 (Ray's number) are story-relevant, but are irrelevant to solving the story problem (how many pounds Ray lifted). If *Moved by Reading* helps children to understand the story in a way that constrains problem solving, then there should be a reduction in misuse of the irrelevant information.

Focusing on the data from the third day of the experiment in which the children used IM during story problem solving, children who had been trained in *Moved by Reading* correctly solved 44% of the problems, whereas the children in the control condition solved 33% (d = .59). In the *Moved by Reading* condition, children misused irrelevant information 38% of the time, whereas in the control condition, the children misused the irrelevant information 61% of the time (d = .78).

These data strongly support the possibility that *Moved by Reading* teaches a fundamental reading comprehension strategy. That is, even though *Moved by Reading* was taught in the context of narrative comprehension, the same strategies supported comprehension that can be used to solve mathematical story problems. Clearly, there are many other types of text genres and reading goals, and there is no guarantee that *Moved by Reading* will be useful in all of them. On the other hand, if the underlying embodied account of comprehension is correct, then it seems likely that *Moved by Reading* is a fundamental strategy that will apply across many domains and tasks.

Moved by Reading and reading in abstract domains

At this point, the skeptical reader may be thinking: "*Moved by Reading* has been shown to be effective with children reading texts appropriate for children. However, adult reading concerns abstract topics such as government or physics in which there is nothing to manipulate using PM or IM. What would it mean to apply *Moved by Reading* in an abstract context?"

In fact, I think that it is likely that many (if not all) abstract topics are understood using the sort of embodied processes encouraged by *Moved by Reading*. As one example, consider reading a text in physics about centripetal force. When an object is in circular motion, then the force on the object acting toward the center of the circle is given by $F = mv^2/r$, where m is the mass of the object, v is the velocity, r is the radius of the circle, and F is centripetal force. How could information such as this be embodied?

A skilled writer will do something like the following to help the reader understand the equation. "Imagine that you are on roller skates in a parking lot. To stop, you grab a post, and as you fly by, you start to spin around the post. That spinning is circular motion, and the force that you feel in your arms is centripetal force, that is, the force causing the circular motion. The speed of your skating before grabbing the post (v) will affect the centripetal force you that feel in your arms. If you are skating fast, then you will be jerked more vigorously when you grab the post than when you are skating slowly. That is the v^2 part of the equation: The faster you go, the greater the centripetal force once you grab the post (and the more it will hurt). Now imagine that you are wearing a heavy backpack (thus you have greater mass), but that you are skating just as fast as before. Will the force that you feel in your arms when you grab the post be greater or less than without the backpack? In fact, the m part of the equation indicates that the force will be greater: If you are more massive, then it is going to hurt more to grab the post than if you were not wearing any backpack. Finally, imagine that instead of grabbing the post with your hands that you have a rope with a loop, and you lasso the post with the loop while you hold onto the other end of the rope. If the rope is short, then you will be whipped around the post in a tight circle, whereas if the rope is long, your path around the post will be a more leisurely, large circle. In which case will you feel more strain (centripetal force) on the rope and your arms? According to the equation, the radius of the circle (r) acts as a divisor so that the longer the rope, the less the force. You can get a feel for this by thinking about how much centripetal force you will feel while whipping around the post on a short rope compared to the more leisurely drift on a long rope."

Thus the skilled writer helps the reader to index the abstract symbols (F, m, v, and r) to embodied experiences. The imagery that a reader experiences in reading an example such of this is exactly the reader's use of IM.

Of course, not all writers are skilled, and in that case it is up to the reader to find a way to index the symbols to appropriate experiences. When reading in a new domain, such as physics, that can be a daunting task. And that is why so few readers understand centripetal force and other scientific concepts.

Conclusions

How is reading comprehension embodied? When understanding text, the words and phrases are indexed to embodied (that is, perception, action, and emotion) experiences to create a simulation of the content of the text. Because this simulation is in a format intimately related to the body, it can be used to guide action. And why does that matter? By understanding the embodied nature of language comprehension, we can create successful educational interventions such as *Moved by Reading.*

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