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Improving early reading comprehension using embodied CAI

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Abstract An embodied approach to reading comprehension suggests that emerging readers must learn to map words and phrases onto their remembered experiences, but this is made difficult by the necessity of focusing attention on decoding. Having children manipulate toys to correspond to what they are reading overcomes this problem, but introduces its own problem for the classroom, namely having to provide a classroom full of children with manipulative. In this article, we demonstrate that having first- and second-grade children manipulate images of toys on a computer screen benefits their comprehension as much as physical manipulation of the toys. In addition, manipulation on one day facilitates reading in the same domain one week later. These findings encourage the use of manipulation of text-relevant images as an educational technology for enhancing early reading comprehension. The findings also set constraints on theoretical accounts of embodiment while reading.

Keywords Reading comprehension · Embodiment · Educational technology · Emerging readers · Computer aided instruction

Introduction

Overview

What does it mean to comprehend a written text? One answer, based on an embodied approach to cognition, is that successful comprehension requires (a) mapping words and phrases to current or remembered experiences and (b) using syntax to guide the appropriate

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integration of those experiences. These processes are particularly difficult for the emerging reader because learning to read out loud forces attention to decoding orthography into phonology. With attention focused on decoding, there is scant attention to comprehension that is, mapping the words onto experiences. *Moved by Reading* is an intervention designed to address this problem by providing the appropriate experiences while reading and teaching children how to relate the written words to those experiences. Previous work has demonstrated the success of this intervention, but only when children are given the opportunity to directly interact with their environments to produce the experiences. Here we ask whether a computer can provide equally effective experience for the emerging reader.

Two approaches to reading comprehension

An influential theory of reading comprehension was developed by Kintsch (1998). In that theory, comprehension requires the construction and integration of propositions. Each proposition corresponds to a simple idea, and it consists of abstract, symbolic representation of concepts linked by abstract relations such as *give, object*, and *recipient*. This theory has inspired a tremendous amount of research, most of which supports the theory at least in broad outline. Nonetheless, this approach falls prey to the symbol grounding problem, namely, how are the abstract symbols given meaning?

The abstract symbols in Kintsch's theory are similar to the data in a computer memory location, that is, they are arbitrarily related to the symbol's referent. For the computer symbol, meaning is provided by a human observer interpreting the symbol. But, who or what interprets the abstract symbols of the mind? One possibility (see Kintsch 2008; Landauer and Dumais 1997) is that the density of connections among abstract symbols is sufficient to support meaning. However, theoretical analyses (Harnad 1990; Searle 1980) and empirical investigations (e.g., Glenberg and Mehta 2008, in press) suggest that this will not work.

Harnad (1990) uses the "symbol merry-go-round" argument to demonstrate why connections amongst abstract symbols cannot lead to meaning. Imagine that you are arriving in a foreign country, and that you do not speak the local language. At your disposal you have a dictionary written solely in the foreign language without English translations. As you step off the airplane, you see a sign, and you wish to understand its meaning. You look up in the dictionary the first word in the sign. Because the definition is in the foreign language, it does not make any sense to you, thus you look up the first word in the definition, but it too does not help, and so you look up the first word in that definition. From this example, it is clear that no many how many words (abstract symbols) you look up, that is no matter how many relations that you trace amongst the symbols, you will be unable to determine the meaning of the sign solely from relations amongst the symbols. Harnad (and others) suggest that one must step off the symbol merry-go-round by grounding, or mapping, the symbols to something (e.g., bodily experiences) outside of the symbol system.

Glenberg and Mehta (2008, 2009b) investigated this issue empirically. Participants in their experiments memorized four different types of relations (e.g., "can" "has as part") between objects and features. The objects, features, and their frequencies of presentation corresponded directly to a well-known semantic domain, namely two-wheeled vehicles found on campus. Whereas the names of the relations were given to the participants, the name of the domain, the names of the objects, and the names of the features were not revealed to the participants. The question of major interest was whether the participants could induce the domain and objects from the memorized relations alone. The answer was that they could not. In another experiment, participants were given the name of the domain, names of the relations, names of three of six objects (road bike, mountain bike, motorcycle), and names of 14 of the 29 features. Participants memorized relations among both the named and unnamed objects and features. The question of interest was again whether participants could induce the meaning of the unnamed objects and features. They could not. Hence, both logical analysis (Harnad 1990; Searle 1980) and data indicate that meaning cannot arise solely from relations amongst abstract features.

An alternative approach can be developed from the perspective of embodied cognition: high-level cognitive processes (e.g., language, mathematics) are grounded in bodily mechanisms of perception, action, and affect (Barsalou 1999, 2008; Semin and Smith 2008). The Indexical Hypothesis (Glenberg and Robertson 1999; Glenberg and Kaschak 2002) is one such theory. It supposes that language comprehension requires that the abstract symbols of language (i.e., words and syntax) be mapped onto embodied experiences or representations of those experiences. These experiences may be provided by sensing the environment, as when looking at a cup while someone is talking about that cup. Alternatively, these experiences may be provided by perceptual symbols (Barsalou 1999) in memory. A perceptual symbol is an analog representation consisting of the partial re-activation of the same neural systems active when the object was apprehended. A tremendous amount of data from neuroscience (e.g., Glenberg et al. 2008; Pulvermüller 2008) and psychological research (e.g., Glenberg and Kaschak 2002; Zwaan and Taylor 2006) has demonstrated the importance of such grounded representations for language comprehension.

The *Moved by Reading* intervention

On this embodied account of language comprehension, why is reading so much more difficult to acquire than an oral language? To put it differently, how is it that a child is able to decode text and say it out loud, but still not understand (e.g., Oakhill et al. 2003)? One possibility is that during oral language learning, the mapping between symbol (word) and object is commonplace. For example, a mother says, “Here is your cup,” and hands the cup to the infant, or a father says, “Wave bye-bye,” while gesturing the action. In contrast, when learning to read, a child must focus on the letter-sound correspondences and on blending those sounds to produce the proper pronunciation of the word. It is unlikely that the words’ referent is anywhere in the environment, and even when a text may be accompanied by pictures, reference to the pictures is unlikely to be systematic. (Even though sensitive teachers may well point to pictures while the teacher reads to the class, the important behavior is for the child to refer words to grounded experiences, such as pictures, while the child is reading.) In this case, reading becomes a meaningless exercise in word calling, much like trying to read a text in a language one does not understand. Oakhill et al. (2003) demonstrate that a non-negligible proportion of students successfully decode but with little comprehension. That is, reading aloud sentences composed of words in the child’s vocabulary does not guarantee comprehension.

The *Moved by Reading* intervention consists of two types of activities designed to teach children how to map words and phrases onto current and remembered experiences. During the physical manipulation (PM) stage, children read simple texts about activities within a particular scenario (e.g., a farm scenario). In front of the child is a set of toys such as a toy barn, tractor, animals, etc. Critical sentences are cued with a picture of a green traffic light. After the child reads a critical sentence (e.g., “The farmer brings hay to the horse”), the child acts out the sentence using the toys, thus forcing the child to connect words to particular objects and syntactic relations (e.g., who did what to whom) to actions. On a comprehension test following reading, children who engage in PM often perform one to two standard deviations better than children who read the same text, but instead of manipulating the toys, these children re-read critical sentences (Glenberg et al. 2004, 2007; Marley et al. 2007).

Following PM, children are taught to imagine manipulating (IM) the toys. That is, upon seeing the green light, they are taught to imagine how they would interact with the toys to act out the sentence. IM produces gains that are similar in size to those produced by PM (Glenberg et al. 2004; Glenberg 2008). Why does IM work so well? The initial PM procedure conveys to the child what reading is all about, namely, using their experiences to construct mental models that correspond to the text. The IM procedure allows children to take advantage of this knowledge, as well as implicitly encouraging the child to use his or her well-practiced skill of mapping heard words to experience used during oral language understanding.

Moved by Reading on computers

Whereas the *Moved by Reading* intervention could be educationally beneficial, it is limited by the necessity of creating stories that match toys or creating toys that match stories. A second limitation for classroom use is the necessity of having many sets of toys, that is, a set of toys for each individual or group of students. Given that many classrooms are becoming computerized and that many schools have computer laboratories, both of these limitations might be overcome by having a child, while reading, manipulate computer images using a mouse. But, will this sort of computer manipulation be as successful as PM? There are reasons to answer in the negative and the affirmative. On the negative side, manipulating computer images may not be as engaging as manipulating toys. Also, the multisensory experience associated with the toys (e.g., both visual and haptic information) may be important for creating the sort of perceptual symbols needed for IM to be successful. On the positive side, to the extent that success of the intervention depends on (a) mapping words to any sort of meaningful representation and (b) encouraging children to map the syntactic relations to actions, then manipulating images using a computer may be as successful as PM.

In the research reported next, we contrasted three conditions. In all of the conditions, children read texts presented on a computer monitor and after reading pairs of texts they took a short comprehension test. In the PM condition, after reading critical sentences, children turned away from the monitor to manipulate physical toys. In the computer manipulate (CM) condition, children manipulated images on the monitor using the mouse (see Fig. 1a–c). Finally, in the Re-read condition, children re-read critical sentences. In the Re-read condition, a non-manipulable version of the images was available on the screen as in a child's picture book.

On the first day of the experiment, children read four texts. On the second day of the experiment, 1 week later, children were instructed to engage in IM (or silent re-reading in the Re-read condition). Then children read four more texts for which there was no manipulation of images on the screen. The first two of these texts were stories describing events in the same, familiar scenario used on the first day (e.g., farm scenario). The second two stories came from an unfamiliar scenario (e.g., house scenario).

This design allowed us to answer several applied and theoretical questions. Will CM be as effective as PM? Will CM be more effective than Re-read? Will CM lead to effective use of IM on Day 2? Will benefits of IM extend to unfamiliar scenarios? On the theoretical side, do effective embodied representations require activity with real objects?

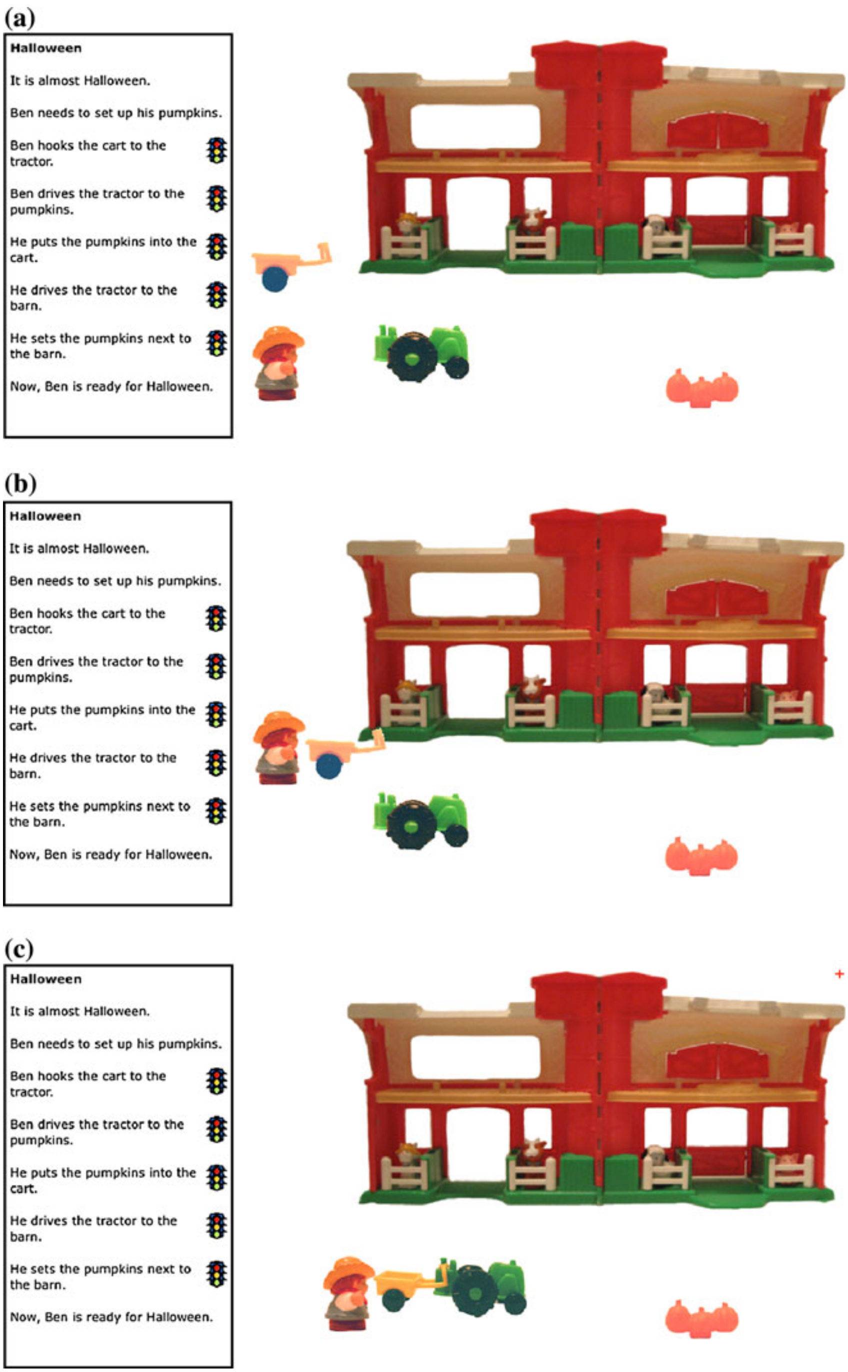

Fig. 1 **a** Screen shot before reading, "Ben hooks the cart to the tractor"; **b** screen shot midway through manipulating for "Ben hooks the cart to the tractor"; **c** screen shot after successfully manipulating for "Ben hooks the cart to the tractor"

Methods

Participants

A total of 53 children in the first- and second-grades were sampled from two sources. One source was a research registry in which parents of children attending the Madison Metropolitan School District could indicate their willingness to participate in research. The second was an after school program in a suburb of Madison, WI. Children from the registry participated in a laboratory room and children from the after school program participated at their school. Parental consent was obtained for all children. Children were randomly assigned to participate in the PM ($n = 14$), CM ($n = 20$), or Re-read ($n = 19$) conditions. Random assignment was done separately for the two sources of participants to ensure no systematic confounding of source and condition.

Materials

For each of two scenarios, we wrote six, eight-sentence stories. Each story included five critical sentences. In addition, for each story we wrote a 10-question yes/no comprehension test. Five of the questions were directed at the critical sentences (e.g., "Did Ben drive the tractor to the pumpkins") and five were directed at information taken from other parts of the story as well as inferable temporal relations (e.g., "Did Ben drive to the barn after he put the pumpkins in the cart") and inferable spatial relations (e.g., "At the end of the story was the tractor at the barn").

Children were randomly assigned to start with one scenario (the Familiar scenario) or the other. The children read four stories from the Familiar scenario on the first day, the remaining two stories from that scenario on the second day (1 week later), and then two stories from the other, Unfamiliar, scenario. The use of the stories was counterbalanced as follows. First, stories were paired. Then, a pair of stories occurred approximately equally often as the first pair on Day 1, the second pair on Day 1, and the first pair on Day 2. Each pair from the second scenario occurred approximately equally often as the second pair on Day 2.

In addition, each scenario had an introduction that was used in all of the conditions. For the introduction, a static picture of the story objects was presented, and the experimenter pointed to and named all of the objects. There was also a five-sentence practice text for each scenario. This text was used on the first day to give children practice reading from the monitor, manipulating, and re-reading. Finally, a three-sentence practice text was created for each scenario and used on the second day to introduce imagine manipulation and silent re-reading. The instructions for imagined manipulation were to imagine interacting with the images (e.g., imagine clicking on an image, dragging it with the mouse, etc.). For the first sentence in the practice text, the experimenter described what was to be imagined. For the remaining sentences of the practice text only, the child described what he or she imagined. If the child did not describe interacting with the images, the child was corrected.

Description of the computer software

The experiments were conducted using a JavaScript-powered Web application that runs in a standard Web browser (e.g., Mozilla Firefox). No additional software needs to be downloaded or installed on a local computer. The Web page displays the sentences in a box on the left side of the screen, with a traffic light icon next to the critical sentences. The right side of the screen displays a static background image for each scenario (e.g., a barn in the farm scenario), and in the foreground, small images represent the key participants and objects in the scenario. For these experiments, the images are high quality photographs of the same toys used in our PM studies.

When the child reaches a critical sentence, he or she must click on the image of the correct object to manipulate (this is akin to picking up the correct toy in a PM study). Clicking anywhere else does nothing. For example, given the sentence “Ben hooks the cart to the tractor,” the child must click on Ben, the farmer. Upon doing so, the image becomes stuck to the mouse cursor, and the child may release the mouse button. (Young computer users may not have mastered the concept of dragging yet.) With an image locked onto the mouse cursor, the child must move the mouse to click on the next relevant object or location (in this case, the cart). Now, moving the mouse will move the farmer and the cart together. A hot zone is defined around the relevant location, providing some flexibility in where the next click must occur. After the last necessary click for the sentence, the selected images become unlocked from the mouse and remain in their new locations, although there may be a slight adjustment in the image to depict important details (e.g., the cart appropriately attached to the tractor). In short, the software is designed to allow only correct manipulations, while allowing some room for error in mouse clicking and moving behavior. When all the required manipulations for a sentence are completed, a small indicator appears in the corner of the screen as a sign to the experimenter that the child may start reading the next sentence.

Procedure

On the first day, children were introduced to the Familiar scenario. Following that, they were instructed as to what a green light signified—manipulate the toys for the children in the PM condition, manipulate the computer images the for children in the CM condition, and re-read for children in the Re-read condition. This instruction was followed by presentation of the five-sentence practice text. Children then read two stories from the Familiar scenario. The comprehension test for those two stories was given after reading the second story so that there was a retention interval of several minutes between readings a story and taking the test. The comprehension questions were read aloud by the researcher and the child responded aloud. Neither the texts nor the pictures were available to the children during the testing. Children then read two more stories from the Familiar scenario and they were tested on those two. At the end of the first day, the children selected a small toy.

On the second day (1 week later), children were instructed in IM or silent re-reading using the three-sentence practice text. This practice was followed by children reading two texts from the Familiar scenario. The first of these was presented along with a static picture of the scenario, and the second was read without any picture. The children were then tested on theses two texts. Children then received the introduction to the second, unfamiliar, scenario along with a static picture. Children then read two texts from the Unfamiliar scenario using either IM (for children in the PM and CM conditions) or silent re-reading. The first of these texts was presented along with a static picture and the second had no picture. Because the manipulation of pictures on the second day had no statistically significant effects, it will not be discussed further. Finally, children were tested on the last two texts, given a second toy, and dismissed.

Results

The means (and standard deviations) of most interest are presented in Table 1. From that table, it appears that children in the CM group outperformed children in the other two groups both on Day 1 and on Day 2 for the Familiar scenario, but not for the unfamiliar scenario. Statistical comparisons conducted using a probability of a Type 1 error of 0.05 generally confirmed these impressions. These statistical analyses were conducted using an ANOVA on the proportions correct using child as the unit of analysis. These proportions were obtained by collapsing across all questions (10 per text) for texts in a given condition. For example, the proportion correct for the first day were obtained from the 40 questions asked that day.

In the first analysis, the data from the familiar and unfamiliar texts on Day 2 were combined. There was an effect of Day, in that children did better on Day 1 than Day 2, $F(1,50) = 4.47$. There are several likely, but relatively uninteresting, reasons for this finding. First, Day 1 consisted of stories from one scenario, whereas Day 2 consisted of stories from two scenarios, one of which was relatively unfamiliar. Second, on Day 1, children used a reading strategy (PM, CM, or re-read aloud) that is likely to be more effective than the Day 2 strategy (IM or re-read silently). Third, all of the Day 1 stories were accompanied by manipulable or static pictures, but only half the Day 2 stories were so accompanied.

More interesting is the main effect of condition, $F(2, 50) = 3.59$. Children in the CM condition outperformed those in the Re-read condition ($p = 0.01$). The interaction of Condition and Day was not significant ($p = 0.26$), which implies that the CM condition outperformed the Re-read condition both on Day 1 when children manipulated images or re-read aloud, and on Day 2 when children imagined the manipulation of images or re-read silently.

We performed a similar analysis using the Day 1 data and the Day 2 data from the Familiar scenario only. In this analysis, there was a significant effect of Day, $F(1, 50) = 8.72$, and condition, $F(2, 50) = 3.97$. The children in the CM condition outperformed the children in the Re-read condition ($p = 0.01$) and the PM condition ($p = 0.05$). Again, there was little evidence for an interaction between Day and Condition, $F < 1$. Finally, we analyzed the data from Day 1 and the data from the Unfamiliar scenario on Day 2. There were no significant effects in this analysis.

It should be noted that the data presented in Table 1 are the proportions correct of all test questions, that is, those questions targeting the action sentences and those drawn from other parts of the texts. When the questions targeting the action sentences are considered alone, the pattern of means and pattern of statistical significance are the same as reported above. However, because performance was so high (e.g., on Day 1, the proportions correct were 0.89, 0.95, and 0.87, and on Day 2, familiar scenario the proportions were 0.80, 0.89,

Table 1 Means (and standard deviations) on the comprehension test

Condition on Day 1	Day 1	Day 2 familiar	Day 2 unfamiliar
Physical manipulate (PM)	0.84 (0.11)	0.76 (0.16)	0.82 (0.16)
Computer manipulate (CM)	0.89 (0.06)	0.84 (0.10)	0.85 (0.11)
Re-read aloud	0.80 (0.10)	0.78 (0.11)	0.82 (0.12)
Effect size (d) for CM compared to re-read	1.16	0.56	NS

Note: NS not statistically significant and 0.84, for the PM, CM, and Re-read conditions, respectfully), those data may reflect in part ceiling effects. Consequently, we decided to focus on analyses of all of the questions.

It is of interest that the positive effects of *Moved by Reading* extend beyond the specific sentences for which children engaged in PM or IM, although the effect is expected: PM and IM help the child to build a mental model of the characters and their actions, and this mental model will be useful in understanding all parts of the story. The finding that the benefits of *Moved by Reading* extend to other parts of the text also help to bolster the claim that the intervention enhances not just memory but also comprehension of the text. That is, applying *Moved by Reading* helps the children to answer inference questions, not just better remember parts of texts corresponding to manipulated sentences.

Discussion

Organization

This discussion will be organized around the questions noted at the end of the introductory section, namely, Will CM be as effective as PM? Will CM be more effective than Re-read? Will CM lead to effective use of IM on Day 2? Will benefits of IM extend to unfamiliar scenarios? On the theoretical side, do effective embodied representations require activity with real objects? Finally, we will address the educational implications of this research, and its relation to work on gaming.

Is CM as effective as PM?

One surprise in the results was that children in the CM condition performed at least as well, or even better, than children in the PM condition ($p = 0.09$ considering all of the data, and $p = 0.05$ considering data from Day 1 and the Familiar scenario from Day 2). This effect may reflect disruption in the PM condition caused by having to turn away from the computer screen in order to manipulate the toys. However, it might also be a real effect, and not simply disruption. For example, manipulating images on the screen may help focus the child on how to realize the syntactic relations when the need to grasp and manipulate the objects is obviated. Or, manipulating images on the screen may discourage play so that the child focuses more on the text.[1] This last reason is reminiscent of research on manipulatives in mathematics contexts. Namely, to the extent that the child plays with the manipulative in contrast to using it as a symbol for a mathematical idea, the manipulative interferes with performance (e.g., McNeil et al. 2009).

Is CM more effective than Re-read? Will CM lead to effective use of IM on Day 2?

Children in the CM condition outperformed those in the Re-read condition, and the effect sizes were large enough to be educationally important. On Day 1, the effect size (Cohen's d) of CM compared to re-read was 1.16, where 0.8 is considered a large effect. On Day 2 (IM compared to re-read), for the Familiar scenario, $d = 0.56$ (a medium size effect). There are several reasons why 0.56 may be an underestimate. First, there were only two texts from the Familiar scenario on Day 2, so that there was more error in the measurement

[1] Several children did appear to play with the images in the CM condition. For example, a child might simulate with the mouse a chicken hopping, or hum a ditty while moving an image.

of Day 2 performance compared to Day 1 performance. Second, because of the long, 1-week, retention interval, it is likely that some children forgot some of the scenario information that might have assisted in their imagined manipulation.

It might also be the case that more extensive practice on PM (or CM) might lead to much larger effects of IM compared to re-reading. For example, in Glenberg, Brown, & Levin (2009a) (a) classrooms were randomly assigned to conditions, (b) the classroom teachers delivered the intervention using researcher-prepared lesson plans, (c) the texts were taken from the children's literature rather than written by the researchers, and (d) third-grade children practiced PM seven times distributed over seven weeks, and they practiced IM 13 times distributed across eight weeks (overlapping with the PM practice). For these children, the effect size of IM (compared to children in a control group who read the same texts distributed in the same way) ranged from 1.1 to over 2.

Will benefits of IM extend to unfamiliar scenarios?

For the current data, the answer is clearly no. This answer is in contrast to both Glenberg et al. (2007a, b) and results from the just-described pilot experiment. In both of those projects, children trained on PM for one scenario showed benefits of IM when reading texts from both familiar and unfamiliar scenarios. There were two notable differences between those projects and the current one, however. First, the children received more extensive training in the previous work. Second, the children were older. Thus, although the benefits of IM were limited in the current research, there is reason to believe that IM will transfer to unfamiliar scenarios with greater practice and/or older children.

Do effective embodied representations require activity with real objects?

The finding that CM resulted in performance at least as good as in the PM condition leads to a negative answer. Because much of the embodied cognition literature has demonstrated effects of real physicality, this finding was a surprise. In retrospect, however, there are good reasons for it. First, language itself deals with categories and rough approximations. That is, even a thorough description of an object will not include all the details of its physicality. Thus, indexing a word to a rough approximate representation of the object may often serve comprehension well. Second, there was nothing in the texts that required (for comprehension) more than a rough approximation to the real object. For example, nothing in the text depended on information about weight of an object that might be difficult to obtain from an image. Thus, the opportunity to embody with action the grammatical relations of who did what to whom may have been sufficient to lead to benefits of CM and its transfer to IM.

Finally, this finding is consistent with Triona and Klahr (2003). In that research, children learned the scientific, control of variables strategy (CVS), namely that in an experiment one must manipulate one variable and control all others. Triona and Klahr demonstrated that children learned equally well whether they manipulated a physical apparatus to construct experiments or whether they manipulated virtual objects on a computer screen.

Educational implications

As noted above, pilot work demonstrates effectiveness of the *Moved by Reading* intervention under classroom conditions. However, the need to use physical manipulatives limits the practical implementation of the procedure. The current work demonstrates how that limitation can be overcome using computers, although we must still demonstrate effectiveness of CM under classroom conditions.

It is of interest to note the relation between CM and work on the educational benefits of gaming (e.g., Barab et al. 2007; Gee 2003, 2008). Whereas no list of the characteristics of successful educational games is accepted by everyone, the following characteristics are likely to be included in most lists. Good computer games:

- are experiential and situated as opposed to a routinized and decontextualized (Wideman et al. 2007)
- relatedly, good games provide skills that are best learned as strategies for carrying out meaningful functions (Gee 2007, p. 41)
- successful games motivate by rewards or opportunities for success

Moved by Reading overlaps with these characteristics. Casual observation suggests that children are more enthusiastic readers in the PM and CM conditions [see footnote (1)] than in the Re-read condition. (Work underway is examining motivation more objectively.) Also, the manipulation after each action sentence provides an opportunity for success.

Whereas enhancing motivation may well account for some of the benefits we observed, we think that the real benefit reflects another similarity with games. That is, games help learners to situate their learning, and thereby to ground in that situation the formalisms that they are learning (Barab et al. 2007). Thus, in both *Moved by Reading* and well-designed games, it is likely that the real benefits for learning and comprehending come when the learner is able to break out of Harnad's (1990) symbol merry-go-round by grounding the symbols (words) in current experience, whether that experience is literally physical or the creation of mental models that embody and represent physical experience.

One might ask whether the benefits of *Moved by Reading* demonstrated here are temporary in the sense that as children become more skilled readers they do not need explicit practice in grounding. Also, is *Moved by Reading* beneficial for only the most concrete texts? Surely, most older readers will not need explicit instruction in grounding for the sort of simple texts used here (although that might not be true when reading in a non-native language). However, we believe that, if anything, the problem becomes more severe as children are asked to read and comprehend texts, such as science texts, that do not address common experiences. That is, it is the inability to ground technical terms in their experiences that, in part, makes science texts daunting.

A recently completed experiment (Richmond et al. 2009) demonstrated the benefits of giving students the opportunity to ground written texts while learning the CVS principle studied by Klahr (e.g., Triona and Klahr 2003). In Richmond et al. (2009) fourth grade students heard a presentation about CVS and then they were given the opportunity to apply it. In one condition, children applied CVS by following *written* instructions for how to set up experiments in a particular domain (e.g., variables that control how far a ball rolls). That is, the children literally manipulated the apparatus by following explicit, written instructions. In another condition, children applied CVS by manipulating the same apparatus, but this time the explicit instructions were *read to* the children. Thus, the two conditions were identical in regard to the symbolic information, but only the first group had practice in grounding written material in their actions.

In a transfer task, all children were asked to apply the CVS principle in a new domain (e.g., variables that control how far a spring will stretch). In this transfer task, all children literally manipulated the apparatus to set up experiments by reading texts that outlined (rather than fully describing) the experiments. The dependent variables were (a) how well the child was able to follow the instructions by designing an unconfounded experiment, and (b) how well the child justified the design of the experiment. The major results from this transfer task were that children who had previously read the texts outperformed the children who had previously listened to the texts on both measures.

The Richmond et al. data demonstrate the power of *Moved by Reading* for four educationally relevant problems. First, manipulation is important for readers who are older than the participants used in the current experiments. Second, manipulation is important for when children (and, most likely adults) need to learn from reading rather than learning to read. Third, manipulation is important for learning how to apply an abstract principle. Finally, manipulation appears to facilitate transfer. Thus, much as with well-designed educational games, *Moved by Reading* can help to situate abstract formalisms and that facilitates acquisition and transfer of the formalism.

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References

Barab, S., Zuiker, S., Warren, S., Hickey, D., Ingram-Goble, A., & Kwon, E.-J. (2007). Situationally embodied curriculum: Relating formalisms and contexts. *Science Education, 91*, 1–33. doi:10.1002/sce.20217.

Barsalou, L. W. (1999). Perceptual symbol systems. *The Behavioral and Brain Sciences, 22*, 577–660.

Barsalou, L. W. (2008). Grounded cognition. *Annual Review of Psychology, 59*, 617–645.

Gee, J. P. (2003). *What video games have to teach us about learning*. New York: Palgrave.

Gee, J. P. (2007). *Good video games + good learning: Collected essays on video games learning and literacy*. New York: Peter Lang.

Gee, J. P. (2008). Learning and games. In K. Salen (Ed.), *The ecology of games: Connecting youth, games, and learning*. The John D. & Catherine T. MacArthur foundation series on digital media and learning. Cambridge, MA: The MIT Press.

Glenberg, A. M. (2008). Embodiment for education. In P. Calvo & A. Gomila (Eds.), *Handbook of cognitive science: An embodied approach* (pp. 355–372). Elsevier: Amsterdam.

Glenberg, A. M., Brown, M., & Levin, J. R. (2007a). Enhancing comprehension in small reading groups using a manipulation strategy. *Contemporary Educational Psychology, 32*, 389–399. doi:10.1016/j.cedpsych.2006.03.001.

Glenberg, A. M., Brown, M., & Levin, J. R. (2009a). Improving reading comprehension in the classroom using manipulatives (in preparation).

Glenberg, A. M., Gutierrez, T., Levin, J. R., Japuntich, S., & Kaschak, M. P. (2004). Activity and imagined activity can enhance young children's reading comprehension. *Journal of Educational Psychology, 96*, 424–436. doi:10.1037/0022-0663.96.3.424.

Glenberg, A. M., Jaworski, B., Rischal, M., & Levin, J. R. (2007b). What brains are for: Action, meaning, and reading comprehension. In D. McNamara (Ed.), *Reading comprehension strategies: Theories, interventions, and technologies* (pp. 221–240). Mahwah, NJ: Lawrence Erlbaum.

Glenberg, A. M., & Kaschak, M. P. (2002). Grounding language in action. *Psychonomic Bulletin & Review, 9*, 558–565.

Glenberg, A. M., & Mehta, S. (2008). On the limits of learning from covariation: Structure but not meaning. In M. de Vega, A. M. Glenberg, & A. C. Graesser (Eds.), *Symbol, embodiment, and meaning* (pp. 11–32). Oxford, UK: Oxford University Press.

Glenberg, A. M., & Mehta, S. (2009b). Constraints on covariation: It's not meaning. *Italian Journal of Linguistics,* in press.

Glenberg, A. M., & Robertson, D. A. (1999). Indexical understanding of instructions. *Discourse Processes, 28*, 1–26.

Glenberg, A. M., Sato, M., Cattaneo, L., Riggio, L., Palumbo, D., & Buccino, G. (2008). Processing abstract language modulates motor system activity. *Quarterly Journal of Experimental Psychology, 61*, 905–919. doi:10.1080/17470210701625550.

Harnad, S. (1990). The symbol grounding problem physica D. *Nonlinear Phenomena, 42*, 335–346. doi:10.1016/0167-2789(90)90087-6.

Kintsch, W. (1998). *Comprehension: A paradigm for cognition*. New York: Cambridge University Press.

Kintsch, W. (2008). Symbol systems and perceptual representation. In M. de Vega, A. M. Glenberg, & A. C. Graesser (Eds.), *Symbol, embodiment, and meaning* (p. XXXX). Oxford, UK: Oxford University Press.

Landauer, T. K., & Dumais, S. T. (1997). A solution to Plato's problem: The latent semantic analysis theory of acquisition, induction and representation of knowledge. *Psychological Review, 104*, 211–240. doi:10.1037/0033-295X.104.2.211.

Marley, S. C., Levin, J. R., & Glenberg, A. M. (2007). Improving Native American children's listening comprehension through concrete representations. *Contemporary Educational Psychology, 32*, 537–550. doi:10.1016/j.cedpsych.2007.03.003.

McNeil, N. M., Uttal, D. H., Jarvin, L., & Sternberg, R. J. (2009) Should you show me the money?. Concrete objects both hurt and help performance on mathematics problems. *Learning and Instruction (*in press).

Oakhill, J. V., Cain, K., & Bryant, P. E. (2003). The dissociation of single-word reading and text comprehension: Evidence from component skills. *Language and Cognitive Processes, 18*, 443–468. doi:10.1080/01690960344000008.

Pulvermüller, F. (2008). Grounding language in the brain. In M. de Vega, A. M. Glenberg, & A. C. Graesser (Eds.), *Symbols, embodiment, and meaning* (pp. 85–116). Oxford: Oxford University Press.

Richmond, E. K., & Glenberg, A. M. *Levin.* (2009). Learning science from text: The importance of grounding written words (in preparation).

Searle, J. R. (1980). Minds, brains and programs. *The Behavioral and Brain Sciences, 3*, 417–424.

Semin, G. R., & Smith, R. E. (2008). *Embodied grounding: Social cognitive, affective, and neuroscientific approaches*. New York, NY: Cambridge University Press.

Triona, L. M., & Klahr, D. (2003). Point and click or grab and heft: Comparing the influence of physical and virtual instructional materials on elementary school students' ability to design experiments. *Cognition and Instruction, 21*, 149–173. doi:10.1207/S1532690XCI2102_02.

Wideman, H. H., Owston, R. D., Brown, C., Kushniruk, A., Ho, F., & Pitts, K. C. (2007). Unpacking the potential of educational gaming: A new tool for gaming research. *Simulation & Gaming, 38*, 10–30. doi:10.1177/1046878106297650.

Zwaan, R. A., & Taylor, L. J. (2006). Seeing, acting, understanding: Motor resonance in language comprehension. *Journal of Experimental Psychology. General, 135*, 1–11. doi:10.1037/0096-3445.135.1.1.