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Cognitive factors that influence children's learning from a multimedia science lesson

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Abstract

The present study examined the cognitive factors that influence children's physical science learning from a multimedia instruction. Using a causally coherent text and visual models, we taught 4th- and 7th- grade children about the observable and molecular properties of the three states of water. We manipulated whether the text was read by a tutor (which supports simultaneous encoding of the verbal and visual information, i.e., *temporal contiguity*) or whether children read the text on their own (which supports self pacing and interpretation of the information). Children in each condition received either static or dynamic graphics. Results showed that, regardless of the type of graphics, children demonstrated the greatest learning gains when the text was read to them by a tutor. This effect was more pronounced for the younger children. Thus, conditions that promote integration of verbal and visual information may provide the greatest support to children's learning from a causally coherent multimedia science lesson.

Keywords: Science Learning, Multimedia Instruction, Causal Coherence, Elementary Education.

Introduction

By the 4th grade, national and state standards in the United States require children to learn about the water cycle and states of matter (National Research Council (U.S.), 1996; Project 2061 (American Association for the Advancement of Science), 1993). One central educational concern is that children are often presented with materials that are

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incomplete, inaccurate, and otherwise ineffective (Bar & Galili, 1994). Existing materials designed to teach physical science rarely contain all relevant concepts necessary for an accurate understanding of states of matter, and even when necessary concepts are included, the materials often lack clarity and coherence (Duschl, et al., 2007). This can be devastating to novice students, who are especially dependent on coherence and explicitness during learning (McNamara, Kintsch, Songer, & Kintsch, 1996; Shwartz, Weizman, Fortus, Krajcik, & Reiser, 2008; Stein, Hernandez, & Anggoro, 2010; Stein & Trabasso, 1982; Trabasso & Bouchard, 2000; Trabasso, Secco, & van den Broek, 1984). Another concern, besides the materials themselves, is that learning is greatly affected by a student's capacity to process the information that they receive. Even if the learning materials are coherent and contain all of the relevant concepts, learning may be inhibited if the demands on a student's cognitive resources are too great. The present study focused on this latter issue and examined the conditions that support and hinder children's early learning of physical science. Using materials developed from a theory of complex learning (Stein et al., 2010), we examined how different processing demands affected 4th- and 7th-grade children's learning about the observable and molecular properties of the three states of water.

A theory of complex learning

In previous research, Stein and colleagues used a theory of complex learning to create learning modules designed to teach elementary-school children about the observable and molecular properties of the three states of water (Stein et al., 2010; Stein, Hernandez, Anggoro, & Hedberg, under review). According to this theory, knowledge acquisition in the sciences requires three types of learning: concept learning, causal explanation-based learning, and argument learning.

In *concept learning* (Klausmeier, 1992; Mandler, 2008; Winston, 1986), explicitness is necessary, especially when learners are novices with little or no prior knowledge of the concepts to be learned. The learning materials must describe all dimensions of the concept as well as the dimensions that are not part of the concept (especially when similar concepts exist) (Klausmeier, 1992; Winston, 1986). An explicit compare/contrast procedure must be used to evaluate similar concepts on critical dimensions, especially when error analyses show a high rate of confusion among certain features in two concepts (Klausmeier, 1992). The reason for such explicitness is to achieve an accurate representation of the chosen concepts, and to avoid over- or under-inclusion of members of a category due to faulty knowledge.

Science learning also involves *causal explanation-based learning* (Stein & Levine, 1989; Stein & Trabasso, 1982; Trabasso & Stein, 1997). For example, understanding states of water requires knowledge of the mechanism that causes water to retain its shape and volume in a solid state. Learning about these causal mechanisms provides learners with transferable knowledge that allows them to explain related phenomena, such as how liquid water has a flexible shape but invariant volume. Failing to provide causal explanations, however, results in superficial understanding (Stein & Levine, 1989; Stein & Trabasso, 1982; Trabasso & Stein, 1997), especially in novices who have little or no knowledge of the domain.

Finally, knowledge acquisition in science involves *argument learning*, which emphasizes the correction of learners' misconceptions about newly learned concepts. Many misconceptions occur because of the presence of an incorrect causal explanatory structure that underlies the misconception (e.g., Slotta & Chi, 2006, Vosniadou & Brewer, 1992). Inaccurate beliefs in the domain must be changed and updated. This can be accomplished by providing evidence in favor of the correct concept and showing learners why their incorrect beliefs need to be changed. Thus, in correcting student errors, an entirely new explanatory structure often needs to be acquired (Stein & Miller, 1993; Thagard, 2000).

The benefits and demands of multimedia instruction

These elements of complex learning—concept learning, causal explanation-based learning, and argument learning—cannot be supported through text-based instruction alone. Explicit visual models are needed to teach learners about complex spatial and causal properties and processes, such as the organization, speed, and movement of molecules, that are difficult to convey in words (e.g., Larkin & Simon, 1987). When used properly, visual models have been found to accelerate learning for both children and adults (Gobert & Buckley, 2000; Goldberg & Bendall, 1995), and can benefit learners at different levels of expertise (Goldberg & Bendall, 1995; Jose & Williamson, 2005; Mayer, Hegarty, Mayer, & Campbell, 2005; Tversky, et al., 2008). Recent work on children's learning about states of water has found that the absence of visual models that exemplify core concepts and their relationships reduces comprehension by about 20%, even with a causally-coherent text (Stein et al., under review).

Forming a coherent conceptual representation from visual and verbal information places high demands on the learner's limited cognitive resources. As Mayer and Moreno (2003) discuss, the learner must organize the presented verbal information into a verbal model, the presented images into a visual model, and integrate these two representations into a coherent whole. There are several ways in which students can become overwhelmed during this process (see Mayer & Moreno, 2003, for an extended discussion). For one, each of the processing channels (verbal and visual) can become overloaded. Thus, understanding can be derailed early on by the complexity of processing novel scientific text and images. Another potential source of cognitive overload comes further downstream. If the student is unable to *simultaneously* hold the verbal and visual representations in working memory, then they will be unable to integrate them. Maintaining and combining representations in each channel is therefore critical as well.

Mayer and colleagues have investigated ways to improve multimedia learning by targeting the different sources of cognitive load. To reduce the burden on visual and verbal processing, Mayer and Chandler (2001) broke a science lesson into smaller units and gave the learner control over the pacing of the lesson. Compared to students who received the same information in one continuous stream, the students who could self-pace showed better learning and transfer of knowledge. Thus, self-pacing could reduce the burden on a student's limited cognitive resources and enhance their ability to form verbal and visual models from the lesson.

To reduce the burden on holding and integrating the visual and verbal models, Mayer and Moreno (2003) suggested that text and images should be presented simultaneously. Mayer and Anderson (1991), for example, found that students evidenced better transfer of learning when they received a lesson in which narration accompanied—as opposed to followed—an animation. When text and images are presented simultaneously, the student may be less likely to lose the visual or verbal representations that must be integrated to form a coherent understanding from a multimedia science lesson.

Self-pacing and temporal contiguity have been shown to reduce different sources of cognitive load in multimedia learning, yet common forms of instruction often involve a tradeoff between these two factors. Learning from an illustrated textbook, for example, is ubiquitous at all levels of education. This form of instruction may support self-pacing, since the student has control over how fast they read and progress. Yet, reading from a textbook is low in temporal contiguity, since the text and images are encountered separately. Another common form of instruction involves a tutor or instructor reading to the child. If a tutor takes the same learning materials (text and images) and reads aloud, then temporal contiguity is increased and it may be easier for the student to hold and integrate the visual and verbal components. Yet this could reduce or eliminate the benefits of self-pacing, since the tutor would hold some or all of the control over the pace of reading.

Purpose and overview of research

Given the potential tradeoffs inherent to different ways of presenting the same multimedia science lesson, we sought to test which task, self-reading vs. tutor-reading, provided the most benefit to learners at different grade levels, 4th and 7th grade. We adopted the causally-coherent text from Stein et al. (under review), which was developed using the principles of concept learning, causal coherence, and argumentation discussed earlier. We also used the same visual models as Stein et al., which served to visually illustrate characteristic molecular properties of the three states of water that were verbally described in the text. Because these learning materials are highly explicit and causally coherent, the burden of interpreting the text and images may be relatively low compared to a typical lesson on the same topics. Nevertheless, the content of the lesson may be novel and challenging for children. If interpreting the content of the text and images is the primary challenge that learners face, then a self-paced lesson may be more effective than tutor-paced lesson. However, if the main challenge of the lesson is holding and integrating information across verbal and visual modalities, then tutor-reading could be most effective. Indeed, Stein et al. (under review), which used tutor-read instruction exclusively, found evidence of impressive learning gains in this condition.

The effects of the different conditions could also depend on age. Older students may have greater metacognitive awareness (e.g., Flavell, 2000; Metcalfe & Shimamura, 1994; Schneider, 2008) in addition to greater reading skills and cognitive capacities. Thus, the 7th graders may be more resilient to the demands of processing the visual and verbal components of the lesson and integrating them into a coherent representation. If so, then the effects of reading condition should be especially pronounced for the younger children, who may be most reliant on self-pacing or temporal contiguity.

In addition to the *Self-Read* condition and *Tutor-Read* conditions at each grade level, we also manipulated the nature of the visual models (static vs. dynamic) contained in the lesson as in Stein et al. (under review). It is possible that the effects of condition will be especially pronounced for one type of visual model, for example, the *Tutor-Read* condition may be especially effective when the visual models are dynamic, because the student is better able to attend to changes in the visual models over time. This may be less important in a static image. Thus, we had four experimental conditions: Tutor-Read/Static, Tutor-Read/Dynamic, Self-Read/Static, and Self-Read/Dynamic. Our control group included children who did not receive our instruction but instead received regular, "business-as-usual" classroom instruction.

Method

Participants

Participants were 158 fourth-grade children (*M* = 9 years, 11 months; range = 9 years, 0 months to 10 years, 8 months; 87 boys, 71 girls) and 172 seventh-grade children (*M* = 13 years, 2 months; range = 11 years, 9 months to 14 years, 8 months; 90 boys, 82 girls) recruited from four Chicago Public Schools. Participating schools were a classical magnet school, a math-science magnet school, an arts magnet school, and a neighborhood school. To enroll in magnet schools, children had to satisfy certain requirements specific to each school (e.g., standardized test scores in reading and math, or interest in an academic domain). To enroll in a neighborhood school, children qualified based on the geographical location of their parents' home address. The racial composition of the sample was 43% African-American, 21% Hispanic, 18% White, 10% Asian/Pacific Islander, and 8% Multi-Racial. This distribution roughly paralleled the overall distribution of ethnicity in the Chicago Public Elementary Schools, as we purposely intended.

Materials

We adopted two modules from the learning sequence developed by Stein et al. (under review). The first module introduced and defined matter, the three states of water, and the shape and volume of solid and liquid. This module focused on whether or not the observable properties (i.e., shape and volume) of solid and liquid water change when water is transferred from one container to another. It also explained that gas (i.e., water vapor) is invisible to the human eye, and that to learn about gas requires an understanding of molecules. The second module focused on the organization, speed, and movement of molecules that define each state of water, and then compared and contrasted these properties in each of the three states. Thus, the goal of the two modules was for children to understand that matter has properties that cannot seen by the human eye, that these properties can be visually modeled, and that the three states of water differ from one another in terms of the organization, speed, and movement of molecules. The shape and volume of water vapor were discussed *after* children learned about the molecular properties of the three states of water. Visual depictions of water vapor molecules allowed children to “see” how the invisible properties of molecules in a gaseous state enable gases to take on the shape or volume of any container.

Descriptions of the observable and molecular properties of each state of water were embedded in a causally-coherent sequence such that shape was discussed first, volume next, and the organization, speed, and movement of molecules third. During the presentation of the organization, speed, and movement of water vapor molecules, the changeability of shape and volume were discussed. Direct comparisons were then made between each of the three states, in terms of shape and volume, and the organization, speed, and movement of molecules. Descriptions for the shape and volume in each state are presented in Table 1. Descriptions for the molecular properties of the three states are presented in Table 2.

Table 1. *Observable Properties of Solid and Liquid Water*

	Shape	Volume
Solid	Constant	Constant
Liquid	Changeable	Constant

Table 2. *Molecular Properties of the Three States of Water*

	Organization	Speed	Movement
Solid	Locked in place	Vibrate and jiggle in place	Don’t move out of lattice structure
Liquid	Close and “cling” to other water molecules	Moderate speed	Slip and slide around and over other molecules
Gas	Fill the entire container	Very fast speed	“Fly” around in all directions

The causal coherence of the text becomes important in describing and illustrating how heat energy regulates the speed and movement of molecules, which in turn determines the state of matter. The speed and movement of molecules increases in proportion to the amount of heat energy absorbed by the molecules. After each state was defined in terms of both observable and molecular properties, the three states were contrasted. A solid was presented first, with a description of the speed and movement of molecules. A liquid was presented next, with an explanation of how the speed and movement of molecules increase and why shape is flexible in liquids versus solids. The gaseous state was presented last, with a discussion of how an even bigger increase in energy leads to molecules breaking away from one another, moving rapidly in a random fashion, and taking up all of the volume of a closed container or escaping into the air if the container is opened.

We also adopted the visual models developed by Stein et al. (under review). The static graphics, in the form of JPEG files, presented either as single illustrations (e.g., the lattice structure of solid water ice molecules), or as a series of three snapshots, representing the beginning, middle, and end of an event (e.g., water as a gas being transferred from one container to another). Whenever possible, a series of three static pictures was used so that comparable content was presented in both the Static and Dynamic Graphics conditions. Thus, even though children in the Static Graphics condition never saw speed or movement conveyed dynamically, they did see three snapshots depicting the beginning, middle, and end points of each event sequence. The dynamic graphics, in the form of QuickTime movies, presented actual motion (e.g., liquid water molecules moving over and under one another, water vapor molecules rapidly moving in a container).

The learning modules and assessments were presented on individual MacBook Pro laptops. A data management program, "FileMaker Pro 8" was used to present the text and graphics, to collect pre and posttest assessment data, as well as to code all of the assessment responses. Each study session was audio-recorded on the laptop and on an iPod as a back-up recorder.

Design and Procedure

Children's receptive vocabulary and verbal ability were assessed using the Peabody Picture Vocabulary Test, third edition (PPVT-III). Children's performance on the PPVT was computed in terms of standard scores (4th grade *M* = 103.54, *SD* = 14.77; 7th grade *M* = 101.22, *SD* = 15.30) and percentile rank (4th grade *M* = 58th, *SD* = 29.20*;* 7th grade *M* = 53rd, *SD* = 30.13). These scores showed no difference between girls and boys in either grade. In each grade, children were assigned to one of the five conditions using a stratified randomization procedure. Stratification assignments were based on children's PPVT scores to ensure that vocabulary scores were normally distributed and equivalent across the five conditions at each grade level.

The four experimental conditions were (1) a *Tutor-Read/Static Graphics* condition, where the text was read aloud to the child in conjunction with the presentation of static graphics, (2) a *Tutor-Read/Dynamic Graphics* condition, where the text was read aloud to the child with the presentation of dynamic graphics, (3) a *Self-Read/Static Graphics* condition, where the child read the text aloud in conjunction with the presentation of static graphics, and (4) a *Self-Read/Dynamic Graphics* condition, where the child read the text aloud with the presentation of dynamic graphics. Children in the *Control* group received only pre and posttests, with the same period of time in between the tests as in the experimental conditions.

In each of the experimental conditions, children participated individually, with a trained tutor guiding each child through the learning modules and assessments. All text and accompanying graphics were presented on the computer screen, with the text on the left hand side of a computer screen and the accompanying graphics on the right hand side of the screen. In the Tutor-Read conditions, the experimenter read the text aloud to the child. The child was encouraged to read along silently, but was not required to do so. In the Self-Read conditions, the child read the text aloud to the experimenter. Children in all experimental conditions were also asked to attend to the embedded graphics.

Children in the four instructional conditions participated in five sessions over an eight- to ten-week period of time. In Session 1, the PPVT was administered and demographic data were collected. Session 2 consisted of a *Pretest* that assessed children's knowledge of the States of Water. Session 3 consisted of the presentation of the *First States of*

Water Module (on solids and liquids), immediately followed by an assessment of children's comprehension of the module. Session 4 consisted of the presentation of the *Second States of Water Module* (on gases and comparison across the three states), and a knowledge assessment immediately following the module. Session 5 consisted of the *Posttest* on States of Water knowledge. Post-testing occurred approximated three to four weeks after the completion of Session 4. Children in the Control condition completed all pretests (Sessions 1 and 2) and the posttest (Session 5). During the time between pre and posttests, children in the Control condition participated in their regular classroom instruction.

The pre and posttests included the same items, which were composed of: (1) true/false questions, (2) yes/no questions, (3) explanations for T/F and Y/N answers, (4) short answer questions, and (5) open-ended questions. We began by asking children to name the three states of matter. We then asked 10 questions for each state. For the purposes of our analyses, the relevant questions were the following (using solid water as an example):

1. Did the shape of the solid change when you transferred it from container 1 (short and skinny) to container 2 (tall and wide)? Why or why not?
2. Did the volume of the solid change when you transferred it from container 1 to container 2? Why or why not?
3. True/False: The solid changes shape as it is transferred from container 1 to container 2.
4. True/False: The solid changes volume as it is transferred from container 1 to container 2.
5. True/False: There are more solid molecules in container 2 than there were in container 1.
6. Do you know anything about the molecules that make up solid water ice?
7. What do you know about the molecules that make up solid water ice?

Scoring. FileMaker Pro automatically saved children's pre and posttest responses as the answers were typed into the computer. The computer program automatically scored responses to the T/F and Y/N questions. The remaining responses were scored manually (reliability among three coders was 96%). All questions concerning observable properties of water were T/F or Y/N, whereas all questions concerning molecular properties of water were open-ended, as described below.

For the *observable properties* (i.e., shape and volume) of solid and liquid water, we tabulated children's responses to the T/F and Y/N questions (questions 1-4 listed above). Thus, there were a total of 8 questions, all requiring dichotomous responses. Accuracy scores were computed as the proportion of correct responses out of 8. For the *molecular properties* of each state, children's answers to the three open-ended questions for each state (see question 7 above for solid) were scored with respect to ideal correct responses and "gist" responses, as described below.

Ideal correct responses were explicitly stated in the text. For each state of water, three components constituted a complete, ideal answer. The components focused on the organization, speed, and movement of molecules in each state (see Table 2). In addition to ideal responses, children also provided responses that were acceptable variations on the ideal correct responses (i.e., they maintain the "gist" of the components). For example, some children stated that solid water molecules are frozen in place rather than locked in place. These *gist correct responses* were coded as correct because they showed that children understood the conceptual content, even though they did not use the exact language provided in the text. All correct responses (i.e., ideal and gist), as well as examples of children's actual responses, are listed in Table 3.

Table 3. *Ideal and "Gist" Correct Responses for the Molecular Properties of the Three States of Water*

Solid Water	
Ideal correct responses	Examples
Molecules of solid water are locked in place	*The molecules of solid water [...] locked in place [...]*
Molecules of solid water vibrate; jiggle back and forth	*Molecules of solid water ice do not move, but they still vibrate*
Molecules of solid water do not move over and around one another	*The molecules just vibrate instead of moving around*
Gist correct responses	Examples
Molecules of solid water are frozen	*Um, the molecules [...] they're frozen in place*
Molecules of solid water move slower than molecules of liquid water	*The solid water ice molecules move slower than they would in water*
Molecules of solid water form a lattice structure	*The molecules are [...] in a lattice structure*
The molecular structure of solid water results in a fixed shape	*[...] they stay in the same shape they were put in before they were frozen.*
Liquid Water	
Ideal correct responses	Examples
Molecules of liquid water move at a moderate speed; faster than solid water molecules, but slower than water vapor	*The molecules of liquid water can move but not at a very fast speed [...]*
Molecules of liquid water move around, slip and slide over and under one another	*The molecules of liquid water [...] slide under and over each other [...]*
Molecules of liquid water cling to one another	*The molecules of liquid water stick together.*
Gist correct responses	Examples
Molecules of liquid water are loose, not locked in place	*The molecules of liquid water are not locked together-they are loosely packed*
Molecules of liquid water move around more than molecules of solid water; no mention of slipping and sliding	*The molecules of liquid water [...] move aroun because they aren't solid so they don't stay i place*
Molecules of liquid water do not move fast enough to break away from one another	*Move fast but not fast enough [...] to break far away from each other*

Molecules of liquid water are close together	*The molecules in liquid water [...] stay next to each other.*
Water Vapor	
Ideal correct responses	Examples
Molecules of water vapor move very fast	*[...] moving really, really quickly*
Molecules of water vapor are able to break away from one another	*[...] they can break away from each other [...]*
Molecules of water vapor fill any space in which they are placed (e.g., container, room)	*[...] spread out to make the same size as whatever it's in*

Table 3.(cont.) *Ideal and "Gist" Correct Responses for the Molecular Properties of the Three States of Water*

Gist correct responses	Examples
Molecules of water vapor move around freely in any direction, *without* reference to breaking away from one another	*Water vapor, the molecules can move in any direction they want [...]*
Molecules of water vapor spread out all over, *without* reference to filling an entire space	*They spread out all over the place.*
Molecules of water vapor are loose, with a possible reference to other states	*They're really loose and not compact at all [...]*
The lack of structure for water vapor molecules results in no fixed volume	*They have no fixed volume [...]*
The lack of structure for water vapor molecules results in no fixed shape	*They have [...] no fixed shape [...]*

If a child generated at least one ideal correct response for a question, they were given one point. If they were unable to generate at least one ideal correct response for a question, they were given no points. This procedure was applied to each of the three molecular questions (i.e., for solid water, liquid water, and water vapor), and then the mean of the three scores was computed to obtain the proportion of ideal correct responses across all three states.

Results

Observable properties of solid and liquid water

We expected children to have some prior knowledge about the observable properties of solid and liquid water, especially the older children. Thus, pre-post gain scores on observable properties of solid and liquid should be relatively small compared to gains on learning about molecular properties of the three states. Nevertheless, we compared learning gains on observable properties across the grade levels and conditions.

The results were analyzed with a 2 (Grade: 4th vs. 7th) x 2 (Reading Condition: Tutor-Read vs. Self-Read) x 2 (Graphics Condition: Static vs. Dynamic) between-groups analysis of covariance (ANCOVA). The dependent variable was the pre-post gain score in the proportion of correct responses to Y/N and T/F questions about the shape and volume of solid and liquid water. Standardized scores on the PPVT were included as a covariate.

The analysis revealed a marginally significant effect of Grade, $F(1, 279) = 3.69$, $MSE = .07$, $p = .06$, $\eta_p^2 = .01$, with 4th grade participants showing greater gain scores ($M = .23$, *SD* = .25) than 7th grade participants (*M* = .15, *SD* = .28). No other main effects or interactions approached significance, *F*s < 1.5, *p*s > .25.

In addition to the comparisons between the experimental conditions, we analyzed performance relative to the Control condition. The gain scores for the 7th grade Control group (*M* = .09, *SD* = .22) were marginally higher than those of the 4th grade Control group (*M* = -.02, *SD* = .18), *t*(39) = 1.78, *p* = .08. Gain scores for the 4th grade experimental conditions were significantly higher than those for the 4th and 7th grade Control conditions, *t*s > 2.12, *p*s < .05, with the exception of the 4th grade participants in the Self-Read/Static Graphics condition, whose gain scores (*M* = .18, *SD* = .29) were not significantly greater than the 7th grade Control participants', *t*(39) = 1.18, *p* = .12. Gain scores were generally lower in the 7th grade experimental conditions, as revealed by the ANCOVA. Only the Self-Read/Static Graphics condition (*M* = .19, *SD* = .26) had higher gains than the 7th grade Control condition, *t*(53) = 1.72, *p* < .05. The other 7th grade experimental conditions had higher gains than the 4th grade Control participants, *t*s > 2.70, *p*s < .05, but not the 7th grade Control participants, *t*s < 1.35, *p*s > .09.

Molecular properties of the three states of water

The results were analyzed with a 2 (Grade: 4th vs. 7th) x 2 (Reading Condition: Tutor-Read vs. Self-Read) x 2 (Graphics Condition: Static vs. Dynamic) between-groups analysis of covariance (ANCOVA). The dependent variable was a pre-post gain score in the proportion of ideal correct responses to questions about the molecular properties of the three states of water. Standardized scores on the PPVT were used as a covariate in the analysis. Gain scores were arcsine transformed for the analysis to adjust for the unequal variances between the conditions. The descriptive statistics reported below, however, represent the original scale of measurement.

The results are shown in Figure 1. The ANCOVA revealed a main effect of Grade, *F*(1, 279) = 6.35, *MSE* = .31, *p* < .05, η_p^2 = .02, with 7th grade participants showing greater gain scores (*M* = .70, *SD* = .36) than 4th grade participants (*M* = .64, *SD* = .39). There was also a main effect of Reading Condition *F*(1, 279) = 46.72, *MSE* = .31, *p* < .05, η_p^2 = .14, such that participants in the Tutor-Read condition had greater gain scores (*M* = .77, *SD* = .31) than participants in the Self-Read condition (*M* = .46, *SD* = .41). There was, however, no effect of Graphics Condition, *F*(1, 279) = 0.54, *MSE* = .31, *p* = .46, η_p^2 < .01. The analysis also revealed a marginally significant interaction between Grade and Reading Condition, *F*(1, 279) = 3.15, *MSE* = .31, *p* = .08, η_p^2 = .01. This trend is due to the fact that 4th grade participants showed a larger difference in gain scores between the Tutor-Read condition (*M* = .77, *SD* = .30) and Self-Read condition (*M* = .36, *SD* = .41) than the 7th graders (*M* = .70, *SD* = .36 for Tutor-Read; *M* = .55, *SD* = .40 for Self-Read). No other interactions approached significance, *F*s < 1, *p*s > .30.

Performance of the experimental conditions was also compared to the control conditions. The gain scores for the 4th grade Control group (*M* = .15, *SD* = .24) were equal to those of the 7th grade Control group (*M* = .16, *SD* = .38), *t*(39) = 0.10, *p* = .92. Gain scores for the experimental conditions were significantly higher than those for each of the Control conditions, *t*s > 2.20, *p*s < .05, with the exception of the 4th grade participants in the Self-Read/Static Image condition, whose gain scores (*M* = .16, *SD* = .38) were only marginally greater than the 7th grade Control participants', *t*(42) = 1.28, *p* = .10.

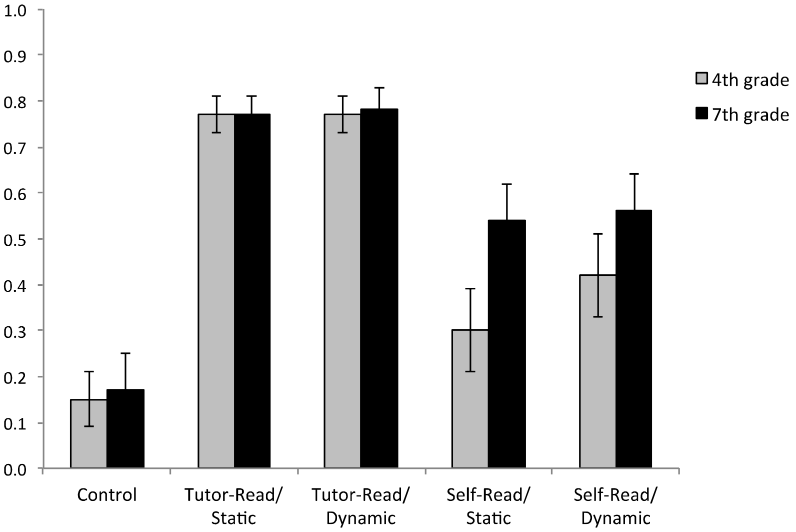

Figure 1. Mean gain scores in the proportion of ideal correct responses to questions about the molecular properties of the three states of water

Discussion

The present study examined the cognitive factors that influence children's learning about the observable and molecular properties of the three states of water by manipulating the delivery of a causally-coherent lesson (Tutor-Read vs. Self-Read) and the nature of the images that the children received (Static vs. Dynamic). The results revealed several important findings. First, children at both grade levels had some prior knowledge about the observable properties of solid and liquid water, and 4th graders showed the greatest improvement at posttest. Second, even though children at both grade levels began with little to no knowledge of molecular properties of the three states water, they were able to learn about these properties through the causally-coherent lesson. Third, even when vocabulary scores were statistically controlled, children in the Tutor-Read condition learned more than those in the Self-Read condition, and this difference was especially pronounced for 4th graders. Finally, at both grade levels children learned equally well regardless of the type of graphics (static vs. dynamic) they received.

In the Introduction, we characterized the two reading conditions in terms of their costs and benefits to different components of multimedia learning. Self-reading provides the benefit of self-pacing the lesson, but does not support integrating of the verbal and visual information. Tutor-reading forfeits control of the pace of the lesson, but the temporal contiguity of verbal and visual information processing supports integration of the two modalities. Our finding of overall greater learning gains in the Tutor-Read condition suggests that integrating the verbal and visual information was the greatest challenge to the children. When a tutor reads to the learner, integration, and thus learning, was enhanced.

It is interesting that the Tutor- vs. Self-Read effect was especially pronounced in the younger age group (though, as noted, this interaction was marginally significant). Younger children have poorer reading skill and metacognitive awareness than older children, and these variables could have contributed to the 4th graders’ exacerbated difficulties in the Self-Read conditions. Although we did not collect data on children’s reading level and metacognitive ability, the Tutor- vs. Self-Read effect was found when children’s vocabulary—a strong predictor of reading ability and general cognitive development—was statistically controlled.

In interpreting these results it is important to take into account potential limitations of the present study. The text that we used was unique because it was designed to be causally coherent. It is possible that children would have benefitted more from self-reading (and therefore self-pacing) if the text lacked this coherence (as is the case in most textbooks), because understanding the content would be more challenging. If the text lacked coherence, the learners would have been required to fill in gaps using their prior knowledge (McNamara et al., 1996), and the more controlled pace of self-reading could have facilitated this process. Another potential concern is that children in the Tutor-Read conditions may have been more engaged in the lesson than those who were self-reading. That is, it is possible that they paid closer attention to both the verbal and visual information and put more effort into integrating the two. However, a tutor was also present to oversee the children who were self-reading. It is equally plausible that children who were self-reading were more engaged because they had to read the text themselves, making the lesson more interactive for them. Finally, our analyses used the children’s grade level/age as a proxy for cognitive control and capacity. Ideally, we would have a measure for each of these variables to test their contributions to the learning outcomes and to rule out other age- and context-related differences, such as everyday experience with water, parental/caregiver expertise in science, and the level of scientific discourse in the children’s broader communities. These are important considerations for future research.

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