Enhancing the Comprehension of Science Text through Visual Analogies

Bryan J. Matlen (bmatlen@andrew.cmu.edu)
Carnegie Mellon University, Department of Psychology
5000 Forbes Avenue, Pittsburgh, PA 15213 USA

Stella Vosniadou (svosniad@phs.uoa.gr)
National and Kapodistrian University of Athens, Department of Philosophy and History of Science
University Town, Athens 161 21, Greece

Benjamin D. Jee (bjee@holycross.edu)
College of the Holy Cross, Department of Psychology
1 College Street, Worcester, MA 01610 USA

Maria Ptouchkina (mptouchkina@u.northwestern.edu)
Northwestern University, Department of Psychology
2029 Sheridan Road, Evanston, IL 60208 USA

Abstract

Instructional analogies are commonly used in science and mathematics text, yet students may have difficulty understanding analogies in the absence of adequate instructional support. In spatially rich domains like geoscience, visual depictions of both the base and target concepts of text analogies (i.e. *visual analogies*) may provide crucial support for students. To test whether visual analogies would be beneficial for learning, 72 fourth- and fifth-grade students were provided a short analogy-enhanced instructional text on plate tectonics that included either pictures of both the base and target concepts (Visual Analogy condition) or the pictures of the target concept only (Target Picture condition). Results indicated that children in the Visual Analogy condition outperformed children in the Target Picture condition on both near and far transfer measures. These results are consistent with recent research suggesting that factors that promote comparison – such as side-by-side presentation of examples – facilitate learning from text.

Keywords: Analogy. Instruction. Science Education. Cognitive Development. Geoscience Education.

Introduction

Analogies pervade thought, thus, they are often used as scaffolds for student learning. Many studies have documented the effectiveness of analogies in math and science learning (Braasch & Goldman, 2010; Clement, 1993; Glynn & Takahashi, 1998; Iding, 1997; McDaniel & Donnely, 1996; Thompson & Opfer, 2010; Vosniadou & Schommer, 1988) and a review on the topic concluded that 12 of 15 studies showed positive effects for analogies in science education (Dagher, 1995). However, while there is general consensus that analogies support learning, substantially fewer studies have addressed how to optimize learning from analogies. Without adequate instructional support – such as guidance during the mapping process (Richland, Holyoak, & Stigler, 2004) or indications of "where the analogy breaks down" (Glynn, 1991) – students may fail to benefit from analogical comparisons (Richland, Zur, & Holyoak, 2007). The present study addresses what design characteristics lead to optimal learning outcomes from analogies. In particular, we assess how visual representations may be used to enhance analogical learning in elementary science education.

Analogical comparison involves aligning two or more representations on the basis of their common relational structure (Gentner, 1983, 2010). When one of the analogs is better understood than the other – as is often the case in analogies used for instruction – information from the familiar case (by convention, termed *the base*) can be projected to the unfamiliar case (by convention, termed *the target*). These analogical inferences provide a powerful way to acquire new knowledge from prior experience.

Research on analogy has revealed that factors that promote analogical comparison also facilitate relational learning (Brown, Kane, & Long, 1989; Christie & Gentner, 2010; Gentner & Namy 1999; Gick & Holyoak, 1983; Kotovsky & Gentner, 1986). For example, Camtrambone & Holyoak (1989) found that when college undergrads were prompted to compare two semantically dissimilar problems that shared a common solution, students were more likely to transfer the solution to a distant analog than students who received the same base examples without prompts to compare them. Recent research has demonstrated that comparison is effective for promoting learning in topics as diverse as mathematics (Rittle-Johnson & Star, 2009), biology (Gadgil, Chi, & Nokes, submitted), architecture (Gentner, Levine, Dhillon, & Poltermann, 2009), and business negotiation (Gentner, Loewenstein, & Thompson, 2001), and that even relatively mild manipulations that promote comparison – such as side-by-side presentation of examples – can facilitate relational learning (Christie & Gentner, 2010; Gentner, Loewenstein, & Hung, 2007; Loewenstein & Gentner, 2002; Oakes & Ribar, 2005).

Although comparison in general has been found to promote learning across a diverse range of topics, the quality of the comparison can be an important factor in influencing students' transfer performance (Gentner et al., 2003). Analogies are most effective when the learner engages in a deep processing of the relational commonalities between base and target concepts (Kurtz, Miao, & Gentner, 2001).

In the case of analogy-enhanced science text, learners may require additional cognitive supports to abstract relevant structural relationships. Research on multimedia learning has suggested the graphical representations in combination with text can aid students' understanding of relationally complex material (Mayer, 1993; Mayer & Anderson, 1992). However, we suggest that providing a visual representation of *both* the base and target – a *visual analogy* -- could facilitate comparison and support analogical learning. Visual analogies may provide more support to processing a text-based analogy compared to viewing an image of the target domain alone. For one, the visual analogy could clarify the properties of the base domain that are relevant to the analogy, potentially highlighting the common relational structure. In addition, by providing an externally available representation of the analogy, the learner can devote fewer cognitive resources to maintaining information about the analogs in memory and more resources to understanding the analogical mapping (Richland, et al., 2007; Sweller, 1994). This may be especially important for analogies involving relatively complex examples. Furthermore, presenting side-by-side images of the base and target may increase the probability that students will engage in comparison.

Despite the potential utility of visual analogies, no studies to our knowledge have systematically assessed whether visual analogies do in fact enhance learning. Our first question was whether science educators commonly use visual analogies. In order to assess the prevalence of visual analogies in real-world educational materials, we conducted an informal analysis of six K – 12 and college textbooks in the fields of geoscience and biology. This analysis revealed that visual analogies were quite rare. For instance, of all analogies found in the text, only 32% were represented graphically[1]. Furthermore, when analogies were accompanied by a graphic, they were most likely to be representations of the target domain (78%). Of all analogies accompanied by a graphic, only a very small proportion of analogies consisted of visual representations of both the base and the target concepts together (19%). Thus, testing the effectiveness of visual analogies could have important implications for improving the use of analogies in science texts.

To assess whether visual analogies enhance learning, in the present study we contrasted the learning outcomes for students who received text-based analogies accompanied by visual analogies (the Visual Analogy condition) with students who received the same text-based analogies accompanied by a picture of the target concept only (Target Picture condition). If visual analogies support learning, children in the visual analogy condition should evidence better retention and transfer of material than children in the target picture condition.

We conducted this research within the context of teaching children about plate tectonics, which appears in many state science standards for 5th and 6th grade students. Plate tectonics are a fundamental mechanism involved in formation of volcanoes and mountains, however, despite its importance, students typically exhibit a variety of misconceptions about the domain (Gobert & Clement, 1998; Gobert, 2004; May, Hammer, & Roy, 2006). Geoscience is also a relatively relationally complex domain, making it a good candidate for analogical instruction (Jee et al., 2010). Given that students' understanding of geoscience 1) is often limited to their everyday experiences, 2) involves relatively relationally complex visuospatial concepts, and 3) is an important component of elementary science education, plate tectonics proved to be a ripe area in which to address whether visual analogies could promote student learning.

Method

Participants

Forty-two 4th grade students (*M* = 9.97 years, *SD* = 0.41 years, 19 girls, 23 boys) and thirty-five 5th grade students (*M* = 10.74 years, *SD* = 0.48 years, 14 girls, 21 boys) from a middle to upper class private elementary school in the Pittsburgh area participated. Five students were excluded from analysis because they did not participate in both the pre-test and post-test phases.

Design

The experiment followed a 2 (condition: Visual Analogy vs Target Picture) x 2 (grade: 4th vs 5th) x 3 (test phase: pre-test, post-test, and extended post-test) mixed design, with test phase as a within-subjects factor.

Materials and Procedure

The study consisted of four phases: 1) the pre-test phase, 2) the instruction phase, 3) the post-test phase, and 4) the extended post-test phase. These phases occurred one day apart from each other, with the exception of phases 2 and 3 that occurred on the same day. In each phase, students sat at desks in their regular science classroom and were told that they would be answering questions about how the Earth's surface changes over time.

During the pre-test phase on day 1, students answered open-ended questions that asked them to 1) indicate the layers of the Earth, 2) describe how volcanoes form, and 3) describe how mountains form. For all questions, students were encouraged to use both drawings and written explanations to describe each process. Students were given as much time as they needed in order to complete the pre-test.

On day 2, students received instruction about plate tectonics and the mechanisms of volcano and mountain formation. Students were randomly assigned to be either in

[1] In prior work, Curtis & Reigeluth (1984) found that 16% of text analogies were represented graphically in science textbooks, and Newton (2002) found a rate of 22%.

the Visual Analogy condition (VA) or the Target Picture condition (TP). Students in the VA condition received analogy-enhanced text accompanied with pictures of the both the base and target of each analogy, while students in the TP condition received the same analogy-enhanced text accompanied by pictures of each target concept (see Figure 1 for an example of visual analogy graphics; in the TP condition, the same target images were presented without the bases). Instruction for both groups consisted of five analogies pertaining to 1) the earth's layers, 2) tectonic plates, 3) convection currents, 4) volcano formation, and 5) mountain formation. Students read through the instruction for 10 minutes, and were encouraged to reread it if they finished early. After the instruction portion, the post-test was administered which was identical in materials and procedure to the pre-test.

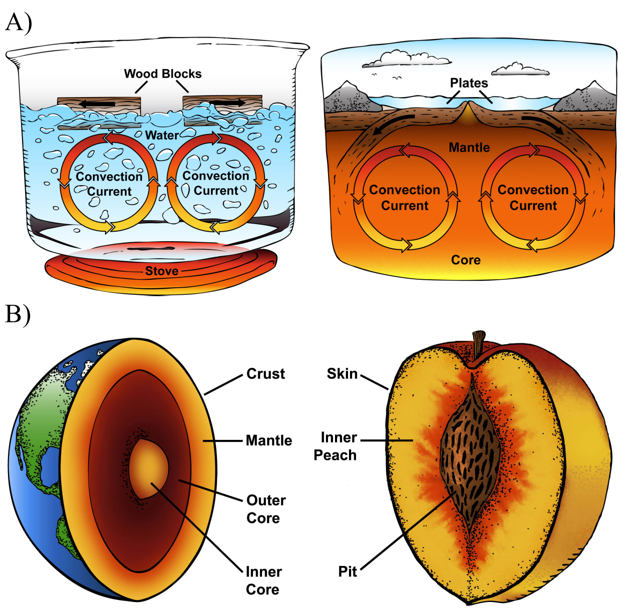

Figure 1. Example of visual analogy graphics for instructions that compare A) Earth's convection currents and plate movement to a boiling pot of water and B) Earth's layers to the layers of a Peach.

On the third and final day, students answered questions on the extended post-test, which consisted of three open-ended questions and three mapping questions. The open-ended questions required short answer responses consisting of one recall question (i.e. "what causes tectonic plate movements?") and two generative questions, which required students to use the information they had acquired during the instruction in novel ways (i.e. "what would happen if the Earth's core stopped generating heat?" and "what would happen if Earth's plates stopped moving?"). The mapping questions asked students to connect corresponding elements for three of the five analogies and to provide a short written explanation of how each pair of elements was related. For example, in the analogy, "the earth is like a peach", elements of the peach (e.g., the pit, the skin, etc.) appeared in written form on the left side of the page, and the relevant elements of Earth (the core, the crust, etc.) were placed to the right in a jumbled order. The students' job was to draw arrows between the analogous parts of the earth and the peach (e.g. the core and the pit) and detail how they were related (e.g. both are solid and/or at the center) (see Figure 2 for an example of a mapping question as it appeared on the test).

Boiling Pot of Water	**Connecting Arrows**	**The Earth**	**In what way are these two parts similar?**
Surface of the Water		Crust	
Water in Pot		Tectonic Plates	
Rising and Falling Water		Mantle	
Stove		Convection Currents	
Wood Blocks		Core	

Figure 2. Example mapping assessment: the students' task was to draw arrows between parts of the base domain and the target domain and to specify how each part was similar.

Scoring

To score the pre- and post-tests, an ideal answer was generated for each question and then broken down into separate "knowledge components" (knowledge components are equivalent to concepts, principles, facts, or skills, etc.). For example, for the question about how mountains form, the ideal answer consisted of indicating that plates move towards each other, that they collide and produce an upward force, that convection currents move the plates, and that each plate is of equal density. Students were assigned a 1 or a 0 for each knowledge component depending on whether it was correctly stated in their response. This same scoring system was used for the three open-ended response questions on the extended post-test. For example, for the question "what would happen if the earth's core stopped producing heat?" students were given a point if they correctly indicated that no new mountains or volcanoes would form, and for whether they indicated that convection currents/plate movements would cease. For the mapping questions, students received a point for correctly drawing an arrow from one concept to the corresponding concept, and a point for correctly indicating how these two concepts were similar. All other responses were assigned a 0.

Results

We first conducted a 2 (condition) x 2 (grade) x 2 (test phase) mixed ANOVA on students' pre- and post-test data. This analysis revealed a main effect of condition $F(1, 68) = 6.47$, $p < .05$, $\eta^2 = .087$ ($M_{VA} = .30$, $M_{TP} = .24$), a main effect of grade $F(1, 68) = 4.59$, $p < .05$, $\eta^2 = .063$ ($M_{fourth} =$

.24, M_{fifth} = .29), a main effect of test phase $F(1, 68) = 264$, $p < .05$ (M_{pre} = .11, M_{post} = .42), $\eta^2 = .795$, and a significant interaction between grade and test phase $F(1, 68) = 11.96$, $p < .05$, $\eta^2 = .15$. Because some research has suggested that analogies might be particularly effective for helping lower ability students (Bean, Singer, & Cowen, 1985; Duit, 1991; Iding, 1997), we conducted separate analyses for 4th and 5th graders. Within the 5th graders, a 2 (condition) x 2 (test phase) mixed ANOVA revealed only a main effect of test phase $F(1, 32) = 151$, $p < .05$, $\eta^2 = .826$, but the effect of condition and the interaction were not significant. However, in the 4th grade students, this same analysis revealed a main effect of test phase $F(1, 36) = 106$, $p < .05$, $\eta^2 = .748$, a main effect of condition $F(1, 36) = 5.39$, $p < .05$, $\eta^2 = .13$ and a significant interaction $F(1, 36) = 5.05$, $p < .05$, $\eta^2 = .123$. Post-hoc tests revealed that, for fourth graders, the effect of condition was significant at the post-tests ($p < .05$), but not at the pre-tests (see Figure 3).

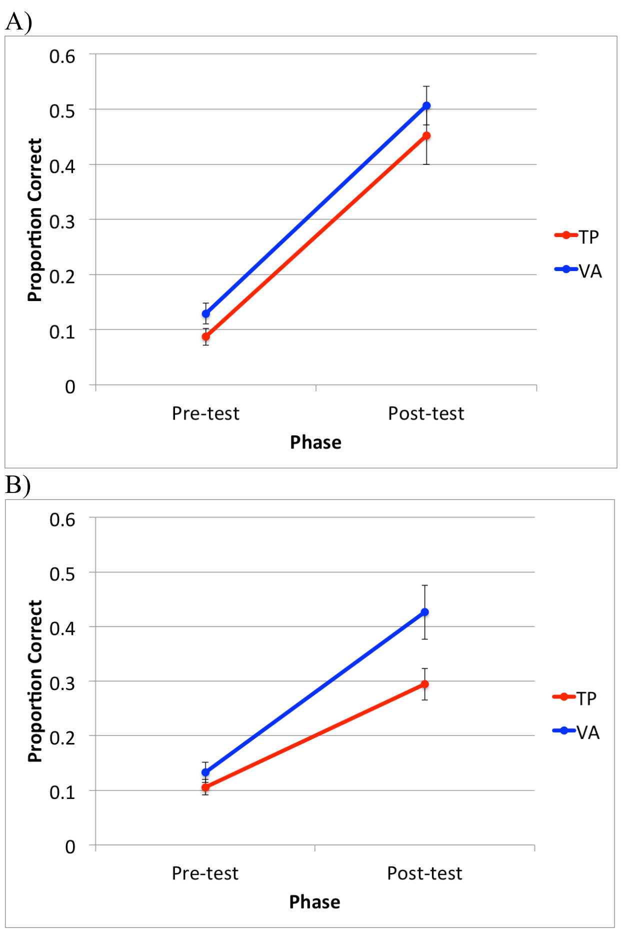

Figure 3. Results of pre- and post-tests by condition in A) 5th graders and B) 4th graders.

Sixty-eight of the 72 students participated in the extended post-test phase. A 2 (condition) x 2 (grade) between subjects ANOVA on the extended post-test scores revealed significant main effects of both grade $F(1, 64) = 9.76$, $p < .005$, $\eta^2 = .13$ (M_{fourth} = .59, M_{fifth} = .74) and condition $F(1, 64) = 7.87$, $p < .01$, $\eta^2 = .11$ (M_{VA} = .73, M_{TP} = .60), however, the interaction was not significant (see Figure 4).

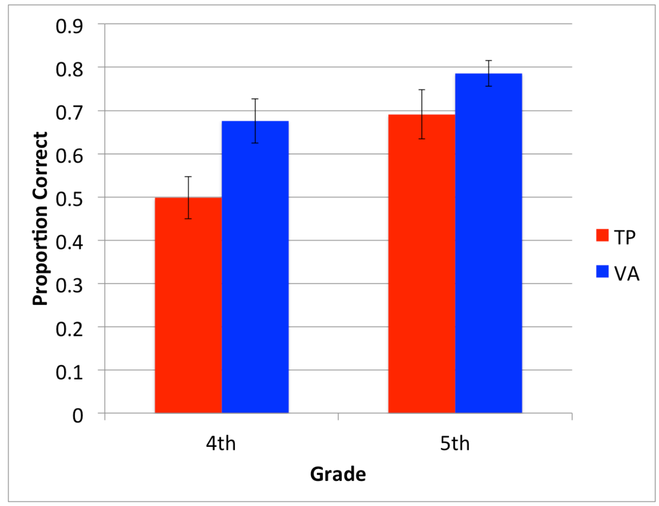

Figure 4. Results of the extended post-tests by grade and condition.

Finally, in order to better understand children's ability to compare aspects of both the base and target concepts, students' scores on the mapping assessments of the extended post-test were analyzed in a 2 (condition) x 2 (grade) between subjects ANOVA. This revealed a significant main effect grade $F(1, 64) = 8.22$, $p < .01$, $\eta^2 = .11$ (M_{fourth} = .71, M_{fifth} = .86) and condition $F(1, 64) = 8.39$, $p = .005$, $\eta^2 = .13$ (M_{VA} = .86, M_{TP} = .71), but the interaction was not significant. We had hypothesized that visual analogies might be more effective for understanding relationally complex concepts. Therefore, we predicted that VA students might outperform TP students on mapping topics such as convection currents (i.e. a more relationally complex concept) as to mapping a topic such as the Earth's layers (i.e. a more relationally simplistic concept). However, independent t-tests of students' performance on the mapping assessment showed that students in the VA condition outperformed students in the TP condition on all analogical mapping assessments (all p's < .05).

Discussion

The aim of the present experiment was to explore whether it is possible for visual analogies to enhance learning more so than pictures of the target concept alone. Across a number of assessment measures, we found that visual analogies were effective for promoting understanding of early geoscience concepts. Specifically, 4th graders retained more information about volcano and mountain formation when they were tested immediately after instruction: this might be considered relatively near transfer, because both materials and time from learning were close to the instruction. However, on a relatively farther transfer test (i.e. the extended post-test) – where students had to apply their knowledge in novel ways – both 4th and 5th grade students who learned from the visual analogy materials outperformed students who received materials with visualizations of only the target picture.

The present study is the first to report an advantage for visual analogies in enhancing students' comprehension of science text. However, it is currently an open question as to why visual analogies led to greater learning. On the one hand, these results are consistent with the notion that factors such as side-by-side presentation of base and target graphics prompts students to engage in analogical comparison. This process would allow students to structurally align the base and target concepts and abstract their relevant relational commonalities. However, the present results could also stem from the fact that the VA condition got to see two pictures, where the TP condition only saw one. Research on multimedia learning has revealed that comprehension of text involving complex relationships is often enhanced by the simultaneous presentation of graphics (e.g. Mayer, 1993). Additionally, students in the VA condition may have simply gotten better at processing the images during the course of the instruction as a result of seeing twice as many images.

Our future work hopes to tease apart these possibilities by replicating the above results and also adding a third condition where students will see base and target images that are difficult to align. Prior research has indicated that comparisons that are highly alignable – representations that share many structural relationships – lead to better learning than comparisons that have low alignability (Gentner, Loewenstein, & Hung, 2007; Gentner et al., 2009). If visual analogies do help students to engage in analogical comparison, we would expect that a high alignability VA condition would outperform a low alignability VA condition on our transfer assessments.

It is interesting to note that, at least on our near transfer assessments, visual analogies helped fourth grade students' comprehension of the text, but they were not more effective than target pictures in helping fifth grade students. It is unlikely that fifth grade students had more prior knowledge of the topic, since both groups scored equally low on the pre-tests. Instead, we surmise that a more general ability, such as reading level, may explain why older students benefited equally from visual analogies and target pictures. However, because we did not have access to students' reading scores or any other measure of general intelligence, this hypothesis remains to be examined in future research.

Both 4th and 5th graders showed higher performance on the extended post-tests when they learned from VA instructions. In particular, our data suggest that the VA group was better able to map relationships from the base and target concepts on our mapping assessments. This finding is consistent with our view that visual analogies might be facilitating students' analogical comparison process. Moreover, we introduce a novel way of assessing learning from analogies: that is, using analogy as an assessment tool rather than just as an instructional tool. The former practice is relatively rare in the literature.

Finally, we caution that it is unlikely that *any* visual analogy – without careful attention to its design – will help students learn from text. In the present study, we took meticulous care to ensure that relevant relationships between base and target concepts were represented in such a way that their relational attributes were supported by their presentation (e.g. relevant relationships were physically aligned on the page). To these ends, we went through multiple iterations with a designer in order to come up with visual analogy graphics. Without great care in designing visual analogies and attention to relational commonalities, graphics may fail to support students learning from science text.

In sum, while the present study is preliminary in nature, it supports the conclusion that carefully designed visual analogies can be effective in helping students learn from science text. Given that visual analogies are used sparsely in real-world contexts, this finding offers promising suggestions for the design of educational materials and adds to a growing body of literature that addresses how analogies can be presented such that they optimize learning in education. Future work will address mechanistic explanations underlying these effects.

Acknowledgments

This work was funded by the Institute of Education Sciences, U.S. Department of Education, under grant R305B040063 to Carnegie Mellon University. We thank Chad Edwards for designing the instructional graphics and the parents, children, school administration and staff that made this research possible.

References

Braasch, J. L. G. & Goldman, R. S. (2010). The role of prior knowledge in learning from analogies in science texts. *Discourse Processes, 47*, 447 – 479.

Bean, T. W., Singer, H. & Cowan, S. (1985). Analogical study guides: Improving comprehension in science. *Journal of Reading*, 246–250.

Brown, A.L., Kane, M.J., & Long, C. (1988). Analogical transfer in young children: Analogies as tools for communication and exposition. *Applied Cognitive Psychology, 3*, 275-293.

Camtrambone, R., & Holyoak, K. J. (1989). Overcoming contextual limitations on problem-solving transfer. *Journal of Experimental Psychology, 15*, 1147 – 1156.

Clement, J. (1993). Using bridging analogies and anchoring intuitions to deal with students' preconceptions in physics. *Journal of Research in Science Teaching, 30*, 1241 – 1257.

Curtis, R.V., & Reigeluth, C.M. (1984). The use of analogies in written text. *Instructional Science, 13*, 99-117.

Dagher, Z. R. (1995). Review of studies on the effectiveness of instructional analogies in science education. *Science Education, 79*, 295 – 312.

Duit, R. (1991). On the role of analogies and metaphors in learning science. *Science Education,* 75, 649–672.

Gadgil, S. M., Nokes, T. J., & Chi, M. T. H. (submitted). Effectiveness of holistic mental model confrontation in driving conceptual change.

Gentner, D., Levine, S., Dhillon, S., & Poltermann, A. (2009). Using structural alignment to facilitate learning of spatial concepts in an informal setting. In B. Kokinov, K. Holyoak, & D. Gentner (Eds.), Proceedings of the second analogy conference (pp. 175–182). Sofia, Bulgaria: NBU Press.

Gentner, D., Loewenstein, J., & Hung, B. (2007). Comparison facilitates children's learning of names for parts. *Journal of Cognition and Development, 8,* 285–307.

Gentner, D. & Namy, L. L. (2006). Analogical processes in language learning. *Current Directions in Psychological Science*, 15(6), 297-301

Gentner, D., Loewenstein, J., Thompson, L. (2003). Learning and transfer: A general role for analogical encoding. *Journal of Educational Psychology*, 95(2), 393-408

Gentner, D. (1983). Structure-Mapping: A theoretical framework for analogy. *Cognitive Science, 7*, 155 – 170.

Gentner, D. (2010). Bootstrapping the mind: Analogical processes and symbol systems. *Cognitive Science, 34*, 752 – 775.

Gick, M.L. & Holyoak, K.J. (1983). Schema induction and analogical transfer. *Cognitive Psychology, 15*, 1-38.

Glynn, S.M. (1991). Explaining science concepts: A teaching-with-analogies model. In S. Glynn, R. Yeany, & B. Britton (Eds.), *The psychology of learning science* (pp. 219-240). Hillsdale, N.J.: Erlbaum.

Glynn, S. M. & Takahashi, T. (1998). Learning from analogy-enhanced science text. *Journal of Research in Science Teaching, 35,* 1129 – 1149.

Gobert, J. D. (2004). The effects of different learning tasks on model-building in plate tectonics: Diagramming versus explaining. *Journal of Geoscience Education, 53,* 444 – 455.

Gobert & Clement (1999). Effects of student-generated diagrams versus student-generated summaries on conceptual understanding of causal and dynamic knowledge in plate tectonics. *Journal of Research in Science Teaching, 36,* 39 – 53.

Iding, M. K. (1997). How analogies foster learning from science texts. *Instructional Science, 25,* 223 – 253.

Jee, B. D., Uttal, D. H., Gentner, D., Manduca, C., Shipley, T., Sageman, B., Ormand, C. J., & Tikoff, B. (2010). Analogical thinking in geoscience education. *Journal of Geoscience Education, 58,* 2-13.

Kurtz, K. J., Miao, C.-H., & Gentner, D. (2001). Learning by analogical bootstrapping. *The Journal of the Learning Sciences, 10,* 417 – 446.

Loewenstein, J., & Gentner, D. (2001). Spatial mapping in preschoolers: Close comparisons facilitate far mappings. *Journal of Cognition and Development*, 2(2), 189-219.

May, Hammer, & Roy (2006). Children's analogical reasoning in a third-grade science discussion. *Science Education, 90*, 316 – 330.

Mayer, R.E. (1993) Illustrations that instruct. In Robert Glaser (Ed) *Advances in Instructional Psychology* (vol. 4). Lawrence Erlbaum Associates, Hillsdale, New Jersey, USA.

Mayer, R.E. & Anderson, R.B. (1992). The instructive animation: Helping students build connections between words and pictures in multimedia learning. *Journal of Educational Psychology, 84*, 444-452.

McDaniel, M. A. & Donnelly, C. M. (1996). Learning with analogy and elaborative interrogation. *Journal of Educational Psychology, 88,* 508 – 519.

Namy, L. L,. & Gentner, D. (2002). Making a silk purse out of two sow's ears: Young children's use of comparison in category learning. *Journal of Experimental Psychology*: General, 131, 5-15.

Newton (2003). The occurrence of analogies in elementary school science books. *Instructional Science, 31*, 353 – 375.

Oakes & Ribar (2005). A comparison of infants' categorization in paired and successive presentation familiarization tasks. *Infancy, 7,* 85 – 98.

Richland, L. E., Holyoak, K. J., & Stigler J. W. (2004). Analogy use in eighth-grade mathematics classrooms. *Cognition and Instruction, 22,* 37 – 60.

Richland, L. E., Zur, O., & Holyoak, K. J. (2007). Cognitive supports for analogies in the mathematics classroom. *Science, 316*, 1128 – 1129.

Rittle-Johnson & Star (2009). Compared with what? The effects of different comparisons on conceptual knowledge and procedural flexibility for equation solving. *Journal of Educational Psychology, 101,* 529 – 544.

Sweller, J. (1994). Cognitive load theory, learning difficulty, and instructional design. *Learning and Instruction, 4*, 295 – 312.

Thompson, C. A. & Opfer, J. E. (2010). How 15 hundred is like 15 cherries. *Child Development*

Vosniadou, S. & Schommer, M. (1988). Explanatory analogies can help children acquire information from expository text. *Journal of Educational Psychology, 80,* 524 – 536.