Do Analogies Increase Learning by Lowering the Dependence on Spatial Ability?

BY

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THESIS

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LIST OF ABBREVIATIONS

PF  Paper Folding Test

CR  Card Rotation Test

FC  Figure Classification Test

DSA Dynamic Spatial Ability Test

ANOVA Analysis of Variance

ANCOVA Analysis of Covariance

Tukey’s HSD Tukey’s Honestly Significant Difference
SUMMARY

Both analogies and diagrams are often included in science texts in order to improve students’ mental-models (Gentner, & Holyoak, 1997; Johnson-Laird, 2004). Yet research looking at the benefits of both devices on learning outcomes has been mixed (Donnelly & McDaniel, 1996; Hegarty, Kriz & Cate, 2003). The current project investigates the possible role of visualization skills in determining whether such devices will help in learning about unobservable science phenomena like weather.

Participants completed measures of visualization skill and read a text about El Nino either with or without (1) an analogy comparing weather to a balloon, and (2) diagrams depicting typical and El Nino weather patterns. After reading, participants wrote an essay explaining the causes of typical and El Nino weather patterns and took a multiple-choice test consisting of inference and application questions. Essays were coded using two measures of mental model quality: coverage (the number of concepts included in essays from a pre-established causal model for the weather patterns), and connectedness (the number of connections participants made between the concepts).

Results from a hierarchical linear regression on scores on the multiple-choice test indicated that the only significant aptitude-by-treatment interaction was between the presence of an instructional analogy and visualization skills. Specifically, there was a stronger relationship between visualization skills and the multiple-choice score when there was no analogy present compared to when an analogy was embedded in the text. Regression analyses were also performed on a composite essay score, essay quality, which yielded the same pattern of results.

While both analogies and diagrams are used to help students develop quality mental-models, this study provides evidence that they are not helping the same individuals.
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I. INTRODUCTION

Compared to other forms of textual discourse, such as narratives, learning from expository science texts is especially difficult for students (Graesser, León, & Otero, 2002). While reading narratives, individuals can bring in their prior knowledge about peoples’ intentions and schemata for world events, which can help them to make predictive and elaborative inferences. Comparatively, students have little prior knowledge about scientific phenomena, and learning about those phenomena is often the purpose for reading expository science texts. Instead of being able to rely on prior knowledge for making inferences, readers must create mental models of the scientific phenomenon (Graesser & Bertus, 1998; León & Penalba, 2002; Johnson-Laird, 2004; Wiley & Myers, 2003). Mental models, as defined by Johnson-Laird (2004), are iconic mental representations of scientific phenomena that have the same structure as the phenomena itself, much like how an architect creates a scale model of a building. Research investigating students’ mental models of mechanics (McCloskey, Caramazza, & Green, 1980) and electrical circuits (Gentner & Gentner, 1983) has shown that one central purpose of creating mental models is to act as simulations that can allow people to understand relations and processes, and make predictions about how systems work.

The construction of these “runnable” mental models (Collins & Gentner, 1987) becomes especially critical for understanding scientific phenomenon that are unobservable due to either scale or invisibility (Jee et al., 2010; Sibley, 2009). Take for example the phenomena of gravitation, electromagnetism, air pressure gradients, and plate tectonics. While individuals may be able to observe the consequences of such phenomena, they are unable to physically see the parts of the systems interacting with one another to create the phenomena. Thus, encoding the parts of the system or process, and how these parts interact as a mental image or series of
mental images, may be especially useful for comprehension.

Consistent with the assumption that many scientific phenomena may be best understood by imaging or visualizing non-observable processes in iconic mental models, many studies have shown that visualization skills are generally positively related to learning and problem solving in STEM (science, technology, engineering and mathematical) domains (2007; Uttal & Cohen, 2012). Two common instructional approaches that have been developed with the goal of supporting students in the construction of higher quality mental models in science are the use of analogies and diagrams. The present study explores the use of these supports, alone and in combination, for learning about air pressure gradients, global weather systems, and El Niño. The main goal of the study is to better understand the conditions that benefit the understanding of students with low spatial visualization skills.

1. Analogies and Learning from Science Texts. Introducing an analogy is one device often included in science texts to help students to understand complex scientific concepts and to specifically promote the development of correct mental models (Gentner, & Holyoak, 1997; Venville & Treagust, 1996). One example of an instructional analogy would be using the notion of what happens when you let air out of a balloon to help teach about air flow patterns that underlie global weather phenomena. In this analogy, the balloon example serves as the familiar base domain and learning about global weather patterns such as El Niño serves as the target domain. The use of instructional analogies to promote understanding has a great deal of intuitive appeal. Students find analogy-embedded texts to be more understandable and interesting (Paris & Glynn, 2004). Analogies are frequently incorporated into instruction to explain difficult or unfamiliar scientific concepts (Curtis & Reigeluth, 1984; Duit, 1991; Glynn, Britton, Semrud-Clikeman, & Muth, 1989). Science teachers embed analogies in their lectures (Baker & Lawson,
2001; Friedel, Gabel, & Samuel, 1990). Textbook authors include analogies in their texts (Curtis, 1988; Curtis & Reigeluth, 1984; Orgill & Bodner, 2006). And, researchers have suggested that analogies are particularly needed when topics deal with processes that cannot be directly perceived and thus can often be known only through comparison to something else (Jee, et al; Sibley, 2009).

The theoretical goal of an instructional analogy is to invoke comparison between the base and target domains. Analogical processing, as outlined by the structure-mapping theory (e. g., Gentner, 1983; Markman, & Gentner, 1997) consists of three steps. In the first step, the reader retrieves prior knowledge about the base domain. For the analogy to be effective, readers must have a good understanding of the base domain prior to engaging in analogical processing (Braasch & Goldman, 2010). In the second step, the reader compares the base domain to the target domain as a function of the relations that they share, and creates structural alignment across the two domains. To do this, the reader must identify the relational structure common to both the base and target, and make the proper correspondences between the two. In the third step, the reader utilizes the correspondences to improve understanding of the target domain using their knowledge of the base domain. There are two ways in which readers do this. The first is termed candidate inferences and consists of the readers taking knowledge that is connected to the common system in the base domain, but not yet in the target domain, and projecting that knowledge onto the target domain (Falkenhainer, Forbus, & Gentner, 1989). Specifically, by engaging in structure-mapping, a reader can import further information from the base to the target, including important spatial, temporal, and causal relations that can serve as the basis for creating mental models of the new phenomenon (Collins & Gentner, 1987). The second mechanism involves readers using the mental model of the base, per se, to run mental
simulations to help flesh out their understanding of the target domain and make predictions (Holland, Holyoak, Nisbett, & Thagard, 1986).

Despite the theoretical reasons that suggest instructional analogies should improve learning, empirical studies comparing learning from texts with embedded analogies to no-analogy comparison conditions have shown inconsistent effects (Alexander & Kulikowich, 1991; Brown, 1992; Clement & Yanowitz, 2003; Donnelly & McDaniel, 1993; Duit, 1991; Gilbert, 1989; Glynn & Takahashi, 1998; Thagard, 1992; Thiele & Treagust, 1994). Some of these studies have shown that a text embedded with an analogy can facilitate learning compared to a comparison text (Brown, 1992; Donnelly & McDaniel, 1993; Glynn & Takahashi, 1998; McDaniell & Donnelly, 1996), while others have failed to find facilitative effects for analogies (Alexander & Kulikowich, 1991; Braasch & Goldman, 2010; Gabel & Sherwood, 1980; Gilbert, 1989; Iding, 1993). Still other studies have shown that introducing analogies can hurt some forms of memory, such as the recall of specific facts from the text (Donnelly & McDaniel, 1993; Yanowitz, 2001), and can prompt misconceptions about the target domain (Zook & di Vesta, 1991; Zook & Maier, 1994).

The variability observed in these studies suggests that the effectiveness of including analogies may be influenced by the either the instructional context that surrounds it or the population that is tested (Glynn, 1991; Iding, 1997; Treagust, 1993). For example, Simons (1984) was able to find benefits in learning from analogies embedded in a long electricity text, but only when coupled with instructions on how to use analogies. Similarly, Paris and Glynn (2004) only found benefits for analogies embedded in science texts when the text included explicit mappings between the concepts in the base and target, as well as images depicting the base and target domains. Alternatively, individual differences in the learners may also influence
the effectiveness of instructional analogies. For example, Braasch and Goldman (2010) examined learning about typical and atypical weather patterns, either with or without an analog involving a deflating tire. In neither experiment was there evidence that learners in the analogy condition developed better understanding of the weather patterns. Instead, they found that any learning benefits from the instructional analogy depended on learners possessing prior knowledge about the base domain.

The present research continues this approach by exploring whether individual differences in visualization skills may also determine the effectiveness of learning from embedded analogies in an expository science text. Because analogies may be especially important for helping students generate mental models that can allow them to run simulations of processes, students with poor visualization skills may specifically benefit from the use of this device. In an initial study (Taylor & Wiley, 2012), we looked at the role of visualization skills on learning about weather patterns and they were positively related to learning about El Niño from a text that did not contain an analogy. However, when the same text included an interleaved analogy about how air flows out of a balloon, there was no relationship between learning outcomes and visualization skills. This finding is convergent with the only other study of learning from analogies that measured spatial ability (Friedel, Gabel, & Samuel, 1990). Although they found no overall differences due to the inclusion of an analogy in a text, students in the plain text condition showed a more positive relationship between spatial visualization skills and learning compared to students in the analogical instruction condition (Friedel, Gabel, & Samuel, 1990).

Thus, one hypothesis to be tested in the present study is whether embedding an instructional analogy into an expository science text may reduce the relationship between spatial visualization skills and learning about El Niño and global weather patterns. Because this subject
matter requires developing a representation of an unobservable process, then providing readers with a familiar analogy might particularly help readers who would otherwise have great difficulty generating an iconic mental model of the phenomenon. For individuals given a plain science text, learning should be strongly positively correlated with spatial visualization skills. However, if instructional analogies help readers map familiar models onto unfamiliar topics, then we expect a weaker correlation or no correlation between visualization skills and learning for individuals who receive instructional analogies.

2. Diagrams and Learning from Science Texts. Other research has suggested that diagrams are another way to promote students’ development of runnable mental models for scientific phenomena. Because what is difficult is developing a representation for the spatial and causal relations among the parts of a scientific system, diagrams have some implicit appeal as an instructional device (see Johnson-Laird, 2004; Martins, 2002). In this way, both analogies and diagrams are theorized to help students in developing mental models.

There is some evidence that pairing verbal/textual information with well-designed diagrams can provide advantages for both memory and understanding when compared to conditions where participants receive only verbal/textual information (Butcher, 2006, Hegarty, Kriz, & Cate, 2003; Mayer & Gallini 1990, Mayer, 2001, Mayer, 2003). For example, studies have found that diagrams that make causal connections explicit with arrows can improve learning (Heiser, & Tversky, 2002; McCrudden, Schraw, Lehman, & Poliquin, 2007). Further, other studies have shown that diagrams and other visualizations can help participants with low visualization skills when learning from texts (Garg, Norman, & Sperotable, 2001; Hays, 1996; Höfler, Sumfleth, & Leutner, 2006; Lee, 2007). One promising form of visualization that has been found to improve understanding of processes and systems are phase diagrams. Phase
diagrams are a special type of diagram that consists of a series of images of the same mechanical device or system, with each image in the series showing a different phase in the movement of the parts of the device/system (Hegarty, Kriz, & Cate, 2003; Tufte, 1997). Hegarty, Kriz and Cate hypothesized that because phase diagrams show the important phases of a process separately, this may allow students to understand a process better than if the same information is displayed as an animation (see also Tversky, Morrison, & Bentracourt, 2002 on the benefits of image sequences over animations). However, although the goal of including diagrams in this study was to support the learning of students with low visualization skills, some studies have shown that participants with high visualization skills are more likely to benefit from these devices (Hegarty, Kriz & Cate, 2003; Mayer & Sims, 1994). Thus, another hypothesis to be tested in the present study is whether embedding phase diagrams into an expository science text might affect the relationship between spatial visualization skills and learning about El Niño and global weather patterns. For individuals given a plain science text without diagrams, learning should be strongly positively correlated with spatial visualization skills. However, if phase diagrams can help learners with poor visualization skills to generate mental models of weather patterns, then we expect a weaker correlation or no correlation between visualization skills and learning for individuals who receive these diagrams.

3. Combining Analogies and Diagrams in Instruction. Finally, there is some research that has looked at both analogies and diagrams in combination. This research suggests that analogical instruction conditions that include visualizations may be more effective. Matlen, Vosniadou, Jee, and Ptouchkina (2011) looked at fourth and fifth grader’s learning of five science topics (earth’s layers, tectonic plates, convection currents, volcano formation, and mountain formation). In this study all students received text-based analogies. What varied was the type of diagrams that they
received along with the texts. Half of the participants received a single diagram with each text depicting the important concepts in the context of the target domain. The other half of the participants received two diagrams with each text, one depicting the concepts in the target domain, and one depicting the concepts in the base domain. They found that for fourth graders, receiving diagrams depicting both the base and target domains was better than receiving the target domain diagram alone. However, no differences between the diagram conditions were found for fifth graders. Chiu and Lin (2005) found that students given diagrams along with a text about electricity outperformed those students who were given only the plain electricity text. In this study, the diagrams provided were depicting analogous domains to the target domain (electrical circuits), which consisted of diagrams depicting a racetrack, water flowing through pipes, and a bridge. In another study, Paris and Glynn (2004) found that students provided with a textual version of an analogy, plus an analogical diagram which depicted the base domain, but labeled the diagram by using terms from the target domain (providing the mapping for students), learned better than students who got either a plain text or a simple analogy (no mapping, no diagram) text. This set of results suggests that combining analogies and images may lead to better learning outcomes. However, none of these studies included individual differences measures which would help to clarify who the two devices are helping, either alone or in combination.

4. Current Study. In the current study participants received a text about global weather patterns. The study was a 2x2 design in which (1) half of participants received an instructional analogy embedded in the text and (2) half of participants received three sets of phase diagrams embedded in the text. Participants wrote essays with the goal of explaining the causes of weather patterns and answered a set of multiple choice questions. Participants also completed a battery
including spatial visualization and reasoning tasks. Aptitude-by-treatment interactions for both manipulations were of most interest. That is, the main goal of this study was to understand if participants showed differing relationships between visualization skills and learning if they were provided with an instructional analogy, phase diagrams, both, or neither in a plain science text.

While both instructional analogies and diagrams are theorized to help promote mental model building, this research will test whether the two scaffolds are helping learners in different ways. Two competing hypotheses can be set up:

1. Effects of the two scaffolds will be similar and may particularly help individuals with low visualization skills to develop higher quality mental models of the scientific phenomena.

2. Effects of the two scaffolds will be seen for different individuals. That is, instructional analogies will be particularly beneficial for facilitating representations of complex, unobservable scientific phenomena for individuals with poor visualization skills. However, as diagrams may require visualization skills as part of the comprehension process, participants with high visualization skills may benefit most from the diagrams being present.
II. METHODS

A. Participants

One-hundred fifty-seven undergraduate students at a large Midwestern university participated as part of a subject pool requirement for Introductory Psychology. Participants were randomly assigned to one of four conditions: Analogy (n = 39), Diagram (n = 41), Both (n = 39), and Plain (n = 38). Participants who failed to comply with the task instructions or were missing data were not retained for final analyses (Analogy n = 9, Diagram n = 6, Both n = 5, Plain n = 6), resulting in a final sample size of 131 (Analogy n = 30, Diagram = 35, Both n = 34, Plain n = 32). Conditions did not differ in proportion of females (70% Females), $\chi^2 = 2.03, p = .56$. They also did not differ in total number of science courses completed ($M = 1.96, SD = 1.72$), ratings for prior knowledge ($M = 2.12, SD = 2.01$), interest ($M = 4.77, SD = 2.82$) or ease of reading ($M = 6.60, SD = 2.19$), $Fs < 1.5, ns$.

B. Design

The study was a between-participants design. The participants were randomly assigned to one of four conditions (Analogy, Diagram, Both, and Plain).

C. Procedure

In the first week of the semester participants enrolled in an Introductory Psychology course completed a prior knowledge question during mass testing. Participants were asked to rate “How much do you know about the El Niño weather pattern?” on a ten-point scale with anchors at one (not much) and ten (very much).

The experimental session was run individually. Participants first completed the timed Paper Folding, Card Rotation and Figure Classification tests. Next, participants read instructions for the main portion of the experiment from a browser window on a computer. All participants
were instructed that they would be reading a text about weather patterns and that they would be
writing an essay. All subjects were given instruction on how to navigate through the pages of the
text. Participants in the diagram condition were further instructed that they would see diagrams,
and told how to navigate between those diagrams. Exact instructions are presented in Appendix
A. Participants proceeded through the text at their own pace. Once they finished reading the text
they were prompted to raise their hand.

When participants indicated they were done reading, the browser window was closed so
that the text was no longer available to participants. Participants then completed the essay task on
paper, followed by the multiple choice test, and then a final survey. Each task was self-paced.
After completing the final survey, participants were directed back to the computer for the DSA
test, followed by the Antisaccade test. After completing the DSA and Antisaccade tests
participants were thanked and debriefed.

The entire experiment took on average 1 hour 10 minutes, with all participants finishing
within 1 hour 30 minutes.

D. Material

1. Spatial Tasks. In order to assess individual differences in spatial reasoning and spatial
visualization skills, a battery of 3 spatial tasks were used: Card Rotation, Figure Classification
and Paper Folding from the *Kit of Factor-Referenced Cognitive Tests* (Ekstrom, French, Harman,
& Derman, 1976). Previous work has shown that Card Rotation loads heavily onto the spatial
visualization factor, Figure Classification loads heavily onto a reasoning factor, and Paper
Folding loads onto both the spatial visualization factor and reasoning factor (Kane et al., 2004;
Kane & Engle, 2003).

   a. Paper Folding Test. A paper version of the Paper Folding test, Part 1, was taken
from the *Kit of Factor-Referenced Cognitive Tests* (Ekstrom, French, Harman, & Derman, 1976). Each item consisted of a left portion which contained a series of squares showing how a square 'paper' has been folded, with the final square indicating where a hole has been punched through the paper, and a right portion which gives five answer choices. The first page contained a set of instructions for the test along with one fully worked out example problem. The second page contained the test, which consisted of 10 items. Participants had 3 minutes to complete the 10 items. Participants’ scores were the number of correct responses out of 10. The Paper Folding test is presented in Appendix B.

b. *Card Rotation Test*. A paper version of the Card Rotation test, Part 1, was taken from the *Kit of Factor-Referenced Cognitive Tests* (Ekstrom, French, Harman, & Derman, 1976). In this task participants are given 10 shapes, each followed by 8 items. Each item is either a rotation, or mirror image and rotation of the shape. The participant has to indicate if each of the items is either the same as the shape (rotation) or different than the shape (mirror image rotation). The first page contained a set of instructions for the test along with three practice problems. The second page contained the test. Participants had 3 minutes to complete the 80 items. Scores were computed as the total number of correct responses out of 80. The Card Rotation test is presented in Appendix C.

c. *Figure Classification Test*. A paper version of the Figure Classification test, Part 1, was taken from the *Kit of Factor-Referenced Cognitive Tests* (Ekstrom, French, Harman & Derman, 1976). In this test, each item presents groupings of 3 figures. The objective for the participant is to induct the rule(s) governing the groupings and then use the rule(s) to categorize 8 novel figures. The first page contained a set of instructions for the test along with one fully worked out problem and one practice problem with
explanation. The next 4 pages presented a total of 14 items. Scores were computed as the total number of correct responses out of 112. Participants had 8 minutes to complete this test. The Figure Classification test is presented in Appendix D.

2. **Base Text.** All participants read the same 1,366 word base text on typical and El Niño weather patterns in the Pacific Ocean adapted from Braasch and Goldman (2010). This text has a Flesch-Kincaid Grade Level of 12 and Reading Ease Score of 42. The text was developed by first creating a causal model of typical and atypical (El Niño) weather patterns in the Pacific Ocean. This causal model included 22 concepts, which are listed in Appendix E. A text was then written to describe weather patterns as a causal relationship between these concepts. The text was broken into seven sections and each section was presented on its own screen. Each page had two links at the bottom of the page. A ‘last page’ link allowed participants to move backward to the previous section of the text, and a ‘next page’ link to move forward to the next section.

3. **Analogy.** The analogy text included 15 additional sentences (305 words) that described the movement of air while inflating and deflating a balloon, which had a Flesch-Kincaid Grade Level of 12 and Reading Ease Score of 48. The balloon analogy was split into three sections and inserted into the weather text at the same location used in prior research (Braasch & Goldman, 2010, Taylor & Wiley, 2012). Specifically, the 3 sections of the analogy were inserted between where the underlying scientific principle was first described as a general rule, and where the principle was contextualized within weather patterns. The base text, with the analogy text italicized, is presented in Appendix F.

4. **Diagrams.** Three series of phase diagrams were developed to visually represent the principles contained in the three sections of the balloon analogy, illustrated in the context of weather patterns. Each of the three series of phase diagrams is included in Appendix G. Because
the concepts in each section of the text increased in complexity, the three series’ differed in the number of diagrams included. The first series, which depicted air flowing from high to low pressure systems, included 3 diagrams. The second series, which depicted air pushing surface water with it as it flowed from high to low pressure systems, included 4 diagrams. The third series, which depicted the transition of air pressure systems and water movement from typical to El Niño weather patterns, included 8 diagrams.

The first diagram of each series appeared at the bottom of the page which contained the relevant section of the text. It still had a link for the previous page, but the 'next page' link was replaced with a 'next diagram' link. Pages with a diagram from the middle of the series presented the same text as the first diagram page, but included a link to move back to the previous diagram and a link to move forward to the next diagram in the series. Pages including the final diagram in each series included a link to move back to the previous diagram and a link to move forward to the next page of the text. This setup forced readers to see every diagram in each series. For text pages directly following a page that included a series of phase diagrams, the 'last page' link directed back to the page containing the first diagram in the series. If a reader chose to return to the previous page, they had to navigate back through the full series of diagrams again.

5. Essay Prompt. The essay prompt was “Please write an essay explaining the following: What are the causes of normal weather patterns across the Pacific Ocean, and what changes during El Niño? Specifically, what are the differences between the East and West Pacific during normal weather patterns and El Niño and what are the consequences of those differences?” This type of essay prompt was used in order to get participants to include a causal model of weather patterns in their essays instead of just providing their recall or summary for the text.

6. Multiple Choice Test. Ten multiple choice questions were developed about the content
including 5 text-based questions and 5 application questions. Text-based questions were developed by pulling information directly from the portions of the text. To answer the questions, participants needed to think about relations between ideas. For example the question:

A great deal of evaporation occurs

   a. above the warm water bulge
   b. above nutrient-rich water
   c. above the Atlantic Ocean
   d. above the equator

can be answered using ideas from this sentence: “Because warm water evaporates faster than cold water, the bulge of warm water in the Western Pacific creates a great amount of evaporation and a great deal of upward air movement, as the warm, moist air rises.”.

Alternatively, application questions were developed by creating new contexts for which participants would have to use ideas from the text in order to answer the question correctly. For example:

During a period of normal weather in the Pacific Ocean an underwater volcano opened up off of the coast of Peru, warming the ocean water in the East Pacific. What would most likely occur while this volcano remains active?

   a. Surface air pressure over that area will increase
   b. Surface air pressure over that area will decrease
   c. Peru will receive almost no rain during this period
   d. Upwelling will increase during this period

This question also uses information from the text, but asks about the concept in an unfamiliar context: underwater volcanoes. All 10 questions are presented in Appendix H.
7. Final Survey. A final survey prompted participants to provide ratings of how easy they found the text to read, as well as how interesting they found the text to be. It also asked them about their strategy use during reading, along with demographic questions (age, gender, linguistic and educational background). The final survey is presented in Appendix I.

In order to develop the strategy-use question, a think-aloud pilot study was conducted. Five participants were asked to think-aloud while both reading the base text as well as while writing their essay and completing the multiple-choice questions. Using information that individuals highlighted and connected during think-alouds, as well as how they attempted to answer the test questions, four profiles were identified related to how learners approached comprehension of the text. The first profile included individuals who specified that they were attending to *isolated facts* because they seemed important or interesting. The second profile included individuals who attended to *parts* of the weather system. They split the information into what was happening at a specific spot (i.e. East Pacific, West Pacific). The third profile included individuals who attended to how parts of the system *interacted* with one another. These individuals highlighted how parts of the weather system were interacting and moving. They often used hand gestures to show these movements, or included image-based language within their think-alouds. The final profile included individuals that simply repeated sentences or ideas directly from the text during think-alouds without adding to them, or explicitly stated that they *did not try* to understand the text while reading. Participants in the current study were asked to indicate which of these strategies they followed. Participants were prompted: “While reading and trying to learn from the text, did you use one of the following strategies? If so, circle the one you used. Please be honest”.

8. Dynamic Spatial Ability Test. An intercept task requiring participants to project the
path and timing of moving objects, was administered to provide a measure of dynamic spatial ability (DSA; Fischer, Hickey, Pellegrino, & Law, 1994; Sanchez & Wiley, 2007). This task runs in a browser window with the dimensions 800 x 400 pixels, and the program itself was written in Java. A screenshot is shown in Appendix J. This task consists of a game-like interface in which a small circular dot (with a diameter of 10 pixels) moves horizontally across the top of the screen from left to right at one of three speeds: 175px/sec, 100px/sec, and 75px/sec. The goal is to hit the moving dot with a ‘missile’ that is shot from the bottom right of the screen by the participant by pressing the SPACEBAR. The missile always moves at a constant velocity of 175px/sec to the point of intersection 350 pixels away. It takes the missile exactly 2 seconds to reach the point of intersection. Thus, in order for a participant to intersect the missile with the horizontally moving dot, he or she must press the spacebar exactly two seconds before the dot is directly above the ‘missile control’. In this task the starting point for the trials is manipulated by adding either 750ms, 1000ms, or 1250ms to each of the preset trial speeds. This creates a total of 9 different trials. The wait-time is defined as the time the participant must wait before pressing spacebar in order for the missile to intercept the circular target. From this, the starting point for every trial can be calculated by the following equation $2(V) + W(V) = SP$, where $V =$ velocity, and $W =$ wait time in seconds, and $SP =$ starting point.

Participants completed each trial type 3 times, resulting in a total of 27 trials. Between each individual trial there is a 5 second countdown displayed for the participant in the upper left hand corner of the screen, indicating when the next target will launch. Prior to test trials, participants receive 5 random practice trials of varying speeds and initial starting point.

Participants were awarded points for every successful interception between the missile and the target. In order to be counted as a successful interception the missile must be within 8
pixels of the circle once it has reached the same y-coordinate. Point values ranged between 20-100 points, in 10 point increments, and point values are assigned based on the trial’s relative difficulty. Relative difficulty is based on the dot’s speed and starting position, where trials in which the circle is moving faster and starts further away are awarded higher point values. If the participant ‘misses’ the target, he or she receives no points, and the dot continues to the edge of the screen, prompting the countdown to begin for the next trial.

9. Antisaccade Test. Participants completed a computerized version of the antisaccade task (Kane, Bleckley, Conway & Engle, 2001) to provide a measure of general cognitive ability. Antisaccade is a measure of attentional control which requires inhibiting an initial response of looking towards a briefly flashed visual stimulus and instead shifting attention towards the other side of the screen. Each trial begins by the participant pressing the spacebar which cues a crosshair to be presented at the center of the screen for 200 to 2000ms. At the end of this period the crosshair disappears and an equal sign is flashed to either the left or right of the crosshair for 100ms. Fifty milliseconds after the disappearance of the equal sign, either a B, P, or R is flashed on the opposite side of the screen for 100ms and then is masked by an H for 50 ms and then by the number “8”. This marks the end of the trial. Participants are asked to accurately identify the letter that was flashed. Participants were given 54 trials. The first 18 were practice and the last 36 were the target trials that were used to compute accuracy scores. An example trial sequence is presented in Appendix K.

E. Initial Data Analyses

1. Individual Differences Constructs. As an initial step in analysis, correlations among the five individual differences measures (Paper Folding, Card Rotation, Figure Classification, Antisaccade, and Dynamic Spatial Ability) were examined. The correlation table is presented in
Table 1. These preliminary results indicated that the three paper-based spatial ability measures acted in accordance with *a priori* predictions: Paper Folding correlated significantly with both Card Rotation and Figure Classification. On the other hand, the Antisaccade and DSA measures did not relate to other individual differences measures as expected. Antisaccade scores failed to relate to either paper folding or figure classification tasks (i.e. all should have been measures related to gF). One possible reason for this failure could be that the distance from the monitor was not controlled. When visual angle is not kept constant, performance on this task may not be a valid measure of attentional control (Kane, Bleckley, Conway & Engle, 2001). Similarly, DSA, a measure of dynamic spatial ability should have shown relations with the paper-based measures of spatial visualization. Because of this failure of Antisaccade and DSA to relate to the main constructs of interest (spatial visualization and reasoning skills), they were not included in the factor analysis for these constructs.

Based on this initial analysis, Paper Folding, Card Rotation and Figure Classification were submitted to a principle axis analysis using a promax rotation with two forced factors. This analysis was used in order to create separate factors for spatial visualization and reasoning skills. Table 2 provides factor loadings for each measure. Because of the higher loadings of Card Rotation on the first factor, this is interpreted as the Spatial Visualization Factor and used as the Spatial Visualization Construct in the learning analyses that follow. Because of the higher loadings of Figure Classification on the second factor, this is interpreted as the Spatial Reasoning Factor and used as the Spatial Reasoning Construct in all learning analyses.

2. Essay Coding Essays provided a measure of the participants’ understanding of the weather phenomenon. The quality of each essay was operationalized both in terms of *coverage* and *connectedness*. In order to measure *coverage*, participants’ essays were coded using an ideal
causal model of weather patterns following Braasch and Goldman (2010). A total of 22 concepts were included in the coding scheme (see Appendix E). Using this coding scheme from Braasch and Goldman, for each essay, the 22 concepts were coded as either being present or absent.

The connectedness of each essay was coded by identifying connections that were made between concepts. Causal statements were those in which a causal relationship between concepts was established. Statements coded as being causal statements would include statements such as ‘A caused B’, ‘A happened due to B’, and ‘B because A’, but also includes causal verbs such as ‘A pushed B’ or ‘A warmed B’. Temporal statements were also coded as connections. Temporal statements used one of the following forms: B after A, A then B, A during B. These types of statements do not indicate causality but are important for understanding how the participant has connected concepts within their representation. The final type of connection that was coded for were implicit relationships. These were coded when two concepts in the pre-established causal model of typical and El Niño weather patterns occurred next to one another within the participant’s essay. Implicit connections could occur within the space of two sentences such that concept A is described in sentence 1 and concept B is then described in sentence 2 or vice versa, or implicit connections could occur within the same sentence such as ‘A and B’. Only true and unique connections were counted, such that if a connection was made that was causal, temporal, or implicit, but was either not a correct relationship (with respect to the pre-established causal model) or had already been mentioned previously within the essay, that relation was not counted again. The total of causal, temporal, and implied relations were summed to create a score for the connectedness of each essay.

On average, participants wrote essays with approximately 6.88 sentences ($SD = 3.16$), 6.87 concepts ($SD = 5.28$) and 2.87 connections ($SD = 2.62$). Two coders rated 25 essays for
both coverage and connectedness and inter-rater reliability was calculated (coverage: Krippendorff’s alpha = .75; connectedness: Krippendorff’s alpha = .77). Once inter-rater reliability was established, one coder rated the rest of the essays.
III. RESULTS

A. Relationships between spatial visualization skills and learning. As shown in Table 3, all three measures of learning were highly correlated. Because performance on the two kinds of multiple choice questions related similarly to both essay measures and spatial visualization skill, suggesting that they were measuring the same thing, these two scores were collapsed for all analyses. Similarly, because performance on the two kinds of essay scores related strongly to each other, a composite essay quality score was calculated for each participant using a principle component analysis with no rotation. This measure is considered a measure of the participants essay quality as it takes into account both the essay coverage, and the number of connections between those concepts included.

Because learning was related to the number of science courses that students reported, as well as the number of sentences included in their essays, these measures are included as covariates in the following analyses. Analyses also entered spatial reasoning scores as a covariate so that the unique role of spatial visualization skills could be examined. Spatial visualization was the main individual difference of interest because both the theories of analogical processing and diagram comprehension emphasize imagining and simulating movement either within a mental model or across phase diagrams.

For each of the learning measures a two-step hierarchical linear regression was run. The main effects and covariates were included in the first step of the analysis, while the interactions were included in the second step. The main goal for analysis was testing for the proposed aptitude-by-treatment interactions on three learning outcome measures; essay coverage, essay connectedness, and multiple choice test performance.
1. Relationship Between Spatial Visualization and Essay Quality. In terms of essay quality, the only significant aptitude-by-treatment interaction was between the presence of an instructional analogy and spatial visualization skills. As shown in Figure 1, there was a stronger relationship between spatial visualization skills and the essay quality when there was no analogy present compared to when an analogy was embedded in the text, $\beta = -0.45, t = -2.31, p < .05$. A simple slopes analysis found that participants in the no-analogy condition showed a positive relationship between spatial visualization and essay connectedness that differed significantly from zero, $\beta = 0.31, t(127) = 3.79, p < .001$. Comparatively, the same simple slope for participants who received an instructional analogy in the weather text did not differ significantly from zero, $\beta = 0.07, t < 1, ns$. As shown in Figure 2, there was no aptitude-by-treatment interaction for the diagram condition. There was also no three-way interaction.

The full model and results are presented in Table 4. Overall the final model was a good fit of the data, $R^2 = .37, F(10, 114) = 6.71, MSE = 17.01, p < .001$, and was a better fit than a model that did not include the interaction terms, $R^2 \text{change} = .06, F \text{change}(4, 14) = 2.49, p < .05$.

2. Relationship Between Spatial Visualization and Multiple Choice Test Performance. The only significant aptitude-by-treatment interaction was between the presence of an instructional analogy and spatial visualization skills. As shown in Figure 3, there was a stronger relationship between spatial visualization skills and multiple choice test scores when there was no analogy present, compared to when an analogy was embedded in the text, $\beta = -0.19, t = -1.96, p = .05$. A simple slopes analysis found that participants in the no-analogy condition showed a positive relationship between spatial visualization and multiple choice test scores that differed significantly from zero, $\beta = 0.32, t(127) = 3.89, p < .001$. Comparatively, the same simple slope
for participants who received an instructional analogy in the weather text did not differ significantly from zero, $\beta = .10$, $t(127) = 1.21$, $ns$. As shown in Figure 4, there was no aptitude-by-treatment interaction for the diagram condition. There was also no three-way interaction.

The full model and results are presented in Table 5. Overall the final model was a good fit of the data, $R^2 = .31$, $F(10, 114) = 5.15$, $MSE = 3.89$, $p < .001$, but did not show significant improvement in fit over a model that did not include the interaction terms, $R^2$ change $= .026$, $F$ change$(4, 14) = 1.07$, $ns$.

3. Summary. Both sets of regression analyses designed to test for aptitude-by-treatment interactions between visualization skills, instructional analogies, and phase diagrams show a consistent pattern of results. Specifically, both found the same aptitude-by-treatment interaction such that individuals who received an analogy embedded in the science text showed no relationship between spatial visualization skills and learning, compared to individuals who did not receive an analogy, who showed a positive relationship. On the other hand, no aptitude-by-treatment interaction was observed for the diagram manipulation. Learning from the science text with or without phase diagrams relied on visualization skills to the same extent.

B. Moderated/Mediation of Learning Outcomes by Visualization Skills and Analogy Condition. A moderated mediation analysis was performed to examine how visualization skills might affect the learning process. Specifically, it was theorized that for texts without an analogy present, the relationship between spatial visualization skills and performance on the multiple choice inference test (including within-text inferences and applications-of-knowledge inferences) would be mediated by the ability to construct quality mental models of the science phenomena presented in the text. This process is represented in the top half of Figure 5. The results showed that once the measure of essay quality (which is being used as a surrogate for mental model
quality), the significant relationship between spatial visualization and performance on the final test was reduced. This shows a partial mediation model for individuals who received science text without an analogy present.

Alternatively, it was hypothesized that individuals who received an analogy in their text would not show the same mediation pattern. Specifically, receiving an analogy allowed participants to engage in processes (namely, structure-mapping) that eliminated the need for spatial visualization skills. Thus, it was hypothesized that there should be no relationship between visualization skills and either mental model quality or multiple choice test scores, nor a mediation effect, but still a relationship between mental model quality and application ability. As presented in the bottom half of Figure 5, this is exactly what was found.

C. Reading Behaviors

1. Reading Time. Participants spent an average of 7.24 minutes ($SD = 2.80$) reading in this study. A two-way (Analogy: Present, Absent) by (Diagram: Present, Absent) ANCOVA was performed with reading time as the dependent measure, and spatial visualization skill, reasoning skill, number of science courses taken, and the number of sentences included in the essay as covariates. In order to understand if reading times differed by manipulation as a function of spatial visualization skill, an analogy by spatial visualization skill, diagram by spatial visualization skill, and an analogy by diagram by spatial visualization skill interaction term were added to the model.

The results indicated that there was a main effect of analogy, such that those who received an analogy took longer to read ($M = 7.87$, $SD = 3.02$) than those who did not receive an analogy ($M = 6.56$, $SD = 2.38$), $F (1, 114) = 13.0$, $MSE = 6.48$, $p < .01$, $\eta^2 = .103$. There was also a main effect of diagram, such that those who received diagrams took longer to read ($M = 7.95$, $SD = 2.80$), $F (1, 114) = 13.0$, $MSE = 6.48$, $p < .01$, $\eta^2 = .103$. There was also
than those who did not receive diagrams ($M = 6.53, SD = 2.38$), $F(1, 114) = 6.431$, $MSE = 6.48, p < .05, \eta^2 = .053$. Spatial reasoning skill was a significant predictor of reading times, $F(1, 114) = 3.903$, $MSE = 6.48, p = .05, \eta^2 = .030$, such that people with lower spatial reasoning skills took longer to read. There were no other significant main effects, and no significant interactions, $Fs < 2$.

This analysis revealed that embedding either an analogy or phase diagrams led to increased reading times, though there was no added slowdown due to them both being included in the text. The most important finding of this analysis was that visualization skill did not influence reading time, nor did it interact with either manipulation. That is, while overall participants did take longer to read the text if it included either an analogy or phase diagrams, the amount of slowdown was the same for participants regardless of visualization skill. It was not the case that low spatial skill participants spent more time on the text with analogies or diagrams compared to individuals with high spatial skills. Thus, the differences in learning that were seen as a function of visualization skills cannot be explained as simple artifacts of the time participants spent on the material.

2. Comprehension Strategies. In order to more fully flesh out what effect instructional analogies had on the processing of the weather text, participants were asked to report which approaches they used when reading the text. Based off pilot work, four options were delineated including attending to isolated facts from the text, attending to separate parts of the system, attending to interactions among the parts of the system, and an option to report not having attempted to comprehend the text.

The prompt used in this study asked “did you use one of these strategies”, implicitly asking for participants to pick a single strategy, but not explicitly disallowing participants to pick
multiple strategies. In fact, 17% of participants endorsed having used more than one strategy. Because some participants endorsed multiple strategies, the independent samples assumption of the Chi-squared test was violated and Cochran’s Q Chi-squared statistic was used for these analyses. As shown in Table 6, strategy use did not differ by condition, Cochran’s Qs < 1.5.

The next set of analyses investigated how strategy use related to learning outcomes using Point-Biserial Correlations. As shown in Table 7, using either the isolated facts or parts comprehension strategies was associated with better learning outcomes. Self-reported use of the interacting and no effort comprehension strategies predicted poorer learning outcomes. In particular, the negative relation between learning and the reported use of the interacting strategy was unexpected. In an attempt to understand this pattern of results, relationships between reported strategy use and individual differences in visualization skills and reasoning were examined. The two strategies with the poorest learning outcomes were more likely to be used by participants with lower visualization and reasoning skills. These results indicate that individuals with high and low spatial skills are approaching the task in fundamentally differently ways.

3. Re-analysis using visualization skills profiles. Because the strategy use analyses above showed differences in the ways high and low skill participants approached this learning task, an exploratory analysis of the effects of the analogy and diagram manipulations was performed using an alternative median-split approach. Spatial visualization scores were used to create high and low spatial visualization skill subgroups. The average number of concepts included in essays as a function of skill level, analogy and diagram condition are shown in Figure 6. Using this way of analyzing the data, the benefit of an analogy is seen most clearly in the low visualization skill group. For low visualization skill participants, those who received the analogy on average did better than those who did not receive an analogy. No such relationship existed for high
visualization skill participants. Instead, participants with high visualization skills benefitted most when the weather text included phase diagrams alone.

A three-way 2 (Analogy: present, absent) by 2(Diagram: present, absent) by 2(Visualization skills: high, low) ANCOVA with spatial reasoning, number of science courses, and number of sentences as covariates indicated that there was a significant interaction between analogy and spatial visualization skill, $F(1, 118) = 6.72, MSE = 17.09, p < .05$. In order to further investigate this two-way interaction, Tukey HSD pairwise comparisons were made between participants who received vs. those who did not receive an analogy, at each level of visualization skill. For participants with low visualization skills, those who received an analogy embedded in the text had better coverage ($M = 7.67, SD = 4.08$) compared to participants that did not receive an analogy ($M = 5.68, SD = 3.65$), $Q = 4.74, p < .05$. For participants with high spatial skills, there were no differences in coverage between participants who received an analogy ($M = 8.38, SD = 5.01$) and those who did not ($M = 9.39, SD = 5.96$), $Q = -0.94, ns$. In addition, there was also a marginally significant three-way interaction between analogy, diagram, and spatial skill, $F(1, 118) = 1.91, MSE = 17.09, p = .17$. Although the three-way interaction did not reach significance, this trend suggests that only the high-skill individuals were able to benefit from the diagrams in this study.

No other main effects or interactions were significant, all other $Fs < 1$. 
IV. DISCUSSION

The purpose of this study was to understand how the comprehension of expository science texts can be improved by including analogies and/or diagrams, by asking what kinds of students these devices might help. In this study spatial visualization skill was the individual difference measure of interest. Consistent with previous findings, a positive relation was found between spatial visualization skill and learning in the plain text conditions. However, presenting an instructional analogy eliminated the relationship between visualization skills and learning (i.e. the correlation no longer significantly differed from zero). Hence, the results showed an aptitude-by-treatment interaction between visualization skill and the presence of an analogical comparison in science text. With respect to the presence of diagrams in the text, results showed no such aptitude-by-treatment interaction. That is, participants who received phase diagrams embedded in the El Niño text showed the same relationship between visualization skills and learning as participants who received no phase diagrams. A second set of analyses showed that neither receiving an instructional analogy nor a set of phase diagrams seemed to prompt students to use different strategies during comprehension. But, these analyses did show that individuals with low visualization skills were more likely to attempt to use the interactions comprehension strategy (attempting to understand how different parts of a system interact with each other), which in turn led to poorer learning outcomes than were seen among students who reported using either the understand-the-parts or attend to isolated ideas strategies. A third phase of analysis approached the results by looking at students with lower visualization skills and higher visualization skills separately. Here the effects of analogy could be localized to learners with lower visualization skills. At the same time, in this analysis there was a trend for the diagrams to be related to better learning outcomes for only students with higher visualization skills.
The two alternative hypotheses tested in this study were that either (1) there would be an attenuation in the relationship between visualization skills and learning with the addition of either an analogy or diagrams into the El Niño text, or (2) there would be an attenuation in the relationship between visualization skills and learning with the addition of an analogy, but no such attenuation with the addition of diagrams into the El Niño text. Looking first at instructional analogies, consistent with previous work (Taylor & Wiley, 2012), and both hypotheses, including an analogy in the El Niño text reduced the relation between spatial visualization skills and learning. Both sets of regressions showed that there was less of a relationship between visualization and learning (essay quality, multiple choice). This conclusion was also supported looking at the median split analyses among individuals with lower spatial skills. This result is consistent with theories suggesting that instructional analogies allow the reader to use the mental model for the base domain when comprehending and making inferences about the target domain (Falkenhainer, Forbus, & Gentner, 1989; Holland, Holyoak, Nisbett, & Thagard, 1986). Because the mental model of the base domain has already been constructed and consists of tangible, familiar parts (compared to the target domain, which consists of unobservable, unfamiliar parts), this process leads to less reliance on visualization skills.

Looking at who benefited from the inclusion of phase diagrams in the El Niño text determines which hypothesis was supported. Across both sets regression analyses, whether or not participants received phase diagrams, they showed the same positive relationship between visualization skills and learning. This consistent positive relationship suggests that only those participants with high visualization skills were able to comprehend the phase diagrams. The median split analysis also provides results consistent with this interpretation, showing that across high and low visualization skill groups, only high visualizers tended to benefit from the inclusion
of phase diagrams. Although this trend did not reach significance, the finding is consistent with other work on diagram comprehension, suggesting that the use of diagrams for learning may be reliant on visualization skill (Hegarty & Just, 1993, Hegarty & Kriz, 2008; Narayanan & Hegarty, 1998). Thus, these results support the second hypothesis that analogies and phase diagrams benefit individuals of varying visualization skills differentially.

In this study, participants in the analogy condition received 305 words of content that participants in the no-analogy condition did not receive. That is, the amount of content was not controlled for in this study. In order to control for length/content between analogy and no-analogy texts, previous researchers have included summary/paraphrases of the information already provided into the no-analogy (Braasch & Goldman, 2010; Iding, 1993), or prompted participants in the no-analogy condition to reread the passage (Yanowitz, 2001). One reason filler information and rereading were left out of the non-analogy text in this study was to preserve external validity. In textbooks, analogies are either given or not given. It would not make sense that authors of a textbook would include additional summary content because they did not include an analogy. The other reason that a no-filler comparison was chosen for this study was the concern that adding in additional content might have had its own effects on processing. Even re-reading information may alter processing in a way that no longer allows for a comparison of a plain science text vs. an analogy enhanced science text. Specifically, reading summaries/paraphrases of textual information and/or rereading may allow for the reader to engage in strategies that would not have been engaged in if they had read either a plain science text with no summary or the analogy text (Rawson & Kintsch, 2005; Reder, & Anderson, 1980).

This study did provide some unexpected results. The first unexpected set of results was the lack of an overall benefit for presenting an analogy on learning outcomes. In both regression
analyses, while there was an interaction between visualization skill and learning for the analogy manipulation, there was no main effect of including an analogy. This combination of results suggests that for whatever gain there was in learning for individuals with lower spatial skills, it was offset by a detriment in learning for high visualization skilled individuals. This phenomenon also presented itself in the median split analysis. Specifically, looking at participants with high visualization skills, only the individuals who did not receive an analogy embedded in the El Niño text were able to benefit from the inclusion of the phase diagrams. There are two possible reasons for this pattern. First, individuals with high spatial visualization skills have the skills necessary to construct iconic mental models that are necessary for good comprehension on their own. It may be that by embedding instructional analogies into the El Niño text, it removed the need to actively construct such mental models, which also removed benefits that would have been gained by the individual for having gone through the process of constructing the mental model for themselves (McNamara, Kintsch, Songer, & Kintsch, 1996). Another possible reason could have been due to the quality of the analog, and misconceptions that may be introduced by the base domain. If a reader constructs a mental model directly from the El Niño text, there should be no misconceptions as to how the process works encoded into it. Alternatively, because no analogy is perfect, and no base domain is a perfect one-to-one match of the target domain, carrying over the mental model of the base domain to the construction of the target domain may lead to the reader including misconceptions about the underlying processes involved in the target domain into their newly constructed mental model of the target domain (Glynn, 1991). Either way, the present results highlight that the benefits of including an analogy to improve expository science text comprehension may be limited.
Another unexpected finding was that students who reported attempting to use an *interactions* strategy to understand El Niño had poorer learning outcomes compared to students who reported using either the *isolated ideas* or the *parts* strategies. Because weather is a dynamic system consisting of moving parts, a strategy that emphasized the interactions between those parts would be the most beneficial. However, further analyses showed that the individuals that were most likely to report attempting to use the *interactions* strategy were those with low visualization skills. That is, there was a mismatch between individual skillset and attempted strategy use. Specifically, tracking and encoding the interactions among the parts of the weather system might depend on being able to visualize the system, and yet the individuals who reported trying to use the strategy were those with low visualization skills. Interestingly, individuals with higher visualization skills were more likely to report using the other strategies.

Visualization skills are an important factor to consider not only for understanding what can contribute to the difficulty of learning about scientific phenomena from expository science texts, but also for designing instructional conditions that may help students to construct better mental models of phenomena. This research showed that embedding an instructional analogy was most beneficial for individuals with low visualization skills, while embedding phase diagrams, to the extent any benefit was seen, seemed to be limited to individuals with high visualization skills. The aptitude-by-treatment interactions observed here provide strong evidence that educators must begin to focus attention on individual differences. It is not simply the case that instructional devices such as analogies will confer the same advantages to all learners. Devices such as analogies can sometimes benefit one group while being neutral to another group, but in other cases, the same devices can in fact be harmful to some individuals. This is consistent with prior work that sometimes embedding an analogy can actually harm
learning (Donnelly & McDaniel, 1993; Taylor & Wiley, 2012; Zook & di Vesta, 1991). An interesting direction for further research will be to investigate why individuals with high visualization skills were harmed by the inclusion of an instructional analogy in the El Niño text. It is possible that simple instructions or changing the timing of the presentation of the analogy could change this effect. It may be that instructions telling participants to only use the analogy if they feel they are having trouble understanding the target domain, or alternatively, by introducing the analogy only after students to attempt to build their mental model of the target domain could allow individuals with high visualization skills to develop mental models without a detriment from the analogy. At the same time, such a condition would still provide support for individuals with lower visualization skills to build their mental model off of the base domain. Alternatively, one could tailor instruction to fit individual profiles. Specifically, by testing for visualization skills during a screening phase, students could be assigned to conditions with the instructional devices that they will most benefit from. A further interesting question that needs to be pursued in future research is the exploration of why sometimes visualizations can be found to help support learning in students with poor visualization skills, whereas other times only the students with better visualization skills seem to be able to benefit from these devices. Many studies have shown that visualization skills are generally positively related to learning and problem solving in STEM (science, technology, engineering and mathematical) domains (see Uttal & Cohen, 2012). The results of this study suggest that we should not ignore this relationship, but also that more work needs to be done to understand how we can change instructional practices to maximize the learning of all students.
V. REFERENCES


### TABLE I

*Pearson Correlation Coefficients for individual differences measures.*

<table>
<thead>
<tr>
<th></th>
<th>Paper Folding</th>
<th>Card Rotation</th>
<th>Figure Class</th>
<th>Antisaccade</th>
<th>DSA Score</th>
</tr>
</thead>
<tbody>
<tr>
<td>Paper Folding</td>
<td>1</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Card Rotation</td>
<td>.34*</td>
<td>1</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Figure Class</td>
<td>.19*</td>
<td>.02</td>
<td>1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Antisaccade</td>
<td>-.01</td>
<td>.06</td>
<td>-.13</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>DSA Score</td>
<td>.08</td>
<td>.13</td>
<td>.03</td>
<td>.14</td>
<td>1</td>
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</tbody>
</table>
TABLE II

*Component Loadings of the Paper-based Individual Differences Measures.*

<table>
<thead>
<tr>
<th>Individual Differences Measure</th>
<th>Component 1 (Visualization)</th>
<th>Component 2 (Reasoning)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Card Rotation</td>
<td>.58</td>
<td>.17</td>
</tr>
<tr>
<td>Paper Folding</td>
<td>.64</td>
<td>.52</td>
</tr>
<tr>
<td>Figure Classification</td>
<td>.15</td>
<td>.43</td>
</tr>
<tr>
<td>Eigenvalue</td>
<td>1.40</td>
<td>.98</td>
</tr>
</tbody>
</table>
**TABLE III**

*Correlations between learning measures and individual differences.*

<table>
<thead>
<tr>
<th></th>
<th>Coverage</th>
<th>Connectedness</th>
<th>MC text</th>
<th>MC application</th>
<th>Num. Science Courses</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coverage</td>
<td>1</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Connectedness</td>
<td>.83*</td>
<td>1</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Text Mult. Choice</td>
<td>.56*</td>
<td>.56*</td>
<td>1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>App. Mult Choice</td>
<td>.54*</td>
<td>.50*</td>
<td>.47*</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>Num. science courses</td>
<td>.19*</td>
<td>.15</td>
<td>-.01</td>
<td>.03</td>
<td>1</td>
</tr>
<tr>
<td>Num. sentences in essay</td>
<td>.48*</td>
<td>.56*</td>
<td>.38*</td>
<td>.33*</td>
<td>.05</td>
</tr>
<tr>
<td>Spatial Reasoning</td>
<td>.28**</td>
<td>.31**</td>
<td>.10</td>
<td>.21*</td>
<td>.04</td>
</tr>
<tr>
<td>Spatial Visualization</td>
<td>.29**</td>
<td>.26**</td>
<td>.25**</td>
<td>.27**</td>
<td>-.01</td>
</tr>
</tbody>
</table>
TABLE IV

*Regression Table for participant’s essay quality*

**Dependent Variable: Essay Quality**

<table>
<thead>
<tr>
<th>Variable</th>
<th>Unstandardized Beta (B)</th>
<th>Std. Error</th>
<th>Standardized Beta (β)</th>
<th>t-value</th>
<th>p-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>(Constant)</td>
<td>-1.440</td>
<td>.228</td>
<td>-6.321</td>
<td>&lt;.001</td>
<td></td>
</tr>
<tr>
<td>Diagram (1= Present)</td>
<td>.285</td>
<td>.208</td>
<td>.142</td>
<td>1.372</td>
<td>.17</td>
</tr>
<tr>
<td>Analogy (1= Present)</td>
<td>.250</td>
<td>.213</td>
<td>.125</td>
<td>1.170</td>
<td>.24</td>
</tr>
<tr>
<td>Spatial Visualization Factor</td>
<td>.305</td>
<td>.213</td>
<td>.232</td>
<td>1.429</td>
<td>.16</td>
</tr>
<tr>
<td>Reasoning Factor</td>
<td>.106</td>
<td>.181</td>
<td>.065</td>
<td>.586</td>
<td>.56</td>
</tr>
<tr>
<td>Number of Science Courses</td>
<td>.044</td>
<td>.023</td>
<td>.139</td>
<td>1.877</td>
<td>.063</td>
</tr>
<tr>
<td><strong>Number of Sentences Written</strong></td>
<td><strong>.165</strong></td>
<td><strong>.024</strong></td>
<td><strong>.517</strong></td>
<td><strong>7.005</strong></td>
<td>&lt;.001</td>
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<tr>
<td>Analogy x Diagram Interaction</td>
<td>-.261</td>
<td>.308</td>
<td>-.116</td>
<td>-.847</td>
<td>.40</td>
</tr>
<tr>
<td><strong>Analogy x Vz Interaction</strong></td>
<td><strong>-.445</strong></td>
<td><strong>.193</strong></td>
<td><strong>-.226</strong></td>
<td><strong>-2.305</strong></td>
<td>.023</td>
</tr>
<tr>
<td>Diagram x Vz Interaction</td>
<td>.171</td>
<td>.201</td>
<td>.105</td>
<td>.848</td>
<td>.40</td>
</tr>
<tr>
<td>Analogy x Diagram x Vz Interaction</td>
<td>-.138</td>
<td>.168</td>
<td>-.071</td>
<td>-.824</td>
<td>.41</td>
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</tbody>
</table>
### TABLE V

*Regression Table for the total number of multiple choice questions answered correctly.*

**Dependent Variable: Multiple Choice Total Correct**

<table>
<thead>
<tr>
<th>Variable</th>
<th>Unstandardized Beta ($B$)</th>
<th>Std. Error</th>
<th>Standardized Beta ($\beta$)</th>
<th>$t$-value</th>
<th>$p$-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>(Constant)</td>
<td>5.28</td>
<td>.41</td>
<td></td>
<td>12.94</td>
<td>&lt;.001</td>
</tr>
<tr>
<td>Diagram (1= Present)</td>
<td>.47</td>
<td>.56</td>
<td>.10</td>
<td>.84</td>
<td>.40</td>
</tr>
<tr>
<td>Analogy (1= Present)</td>
<td>-.63</td>
<td>.57</td>
<td>-.14</td>
<td>-1.11</td>
<td>.27</td>
</tr>
<tr>
<td><strong>Spatial Visualization Factor</strong></td>
<td><strong>1.66</strong></td>
<td><strong>.58</strong></td>
<td><strong>.55</strong></td>
<td><strong>2.85</strong></td>
<td><strong>.01</strong></td>
</tr>
<tr>
<td>Reasoning Factor</td>
<td>-.41</td>
<td>.49</td>
<td>-.11</td>
<td>-.83</td>
<td>.41</td>
</tr>
<tr>
<td>Number of Science Courses</td>
<td>.02</td>
<td>.06</td>
<td>.03</td>
<td>.31</td>
<td>.76</td>
</tr>
<tr>
<td>Analogy x Diagram Interaction</td>
<td>.10</td>
<td>.83</td>
<td>.02</td>
<td>.12</td>
<td>.91</td>
</tr>
<tr>
<td><strong>Analogy x Vz Interaction</strong></td>
<td><strong>-1.01</strong></td>
<td><strong>.53</strong></td>
<td><strong>-.22</strong></td>
<td><strong>-1.92</strong></td>
<td><strong>.06</strong></td>
</tr>
<tr>
<td>Diagram x Vz Interaction</td>
<td>-.17</td>
<td>.55</td>
<td>-.05</td>
<td>-.31</td>
<td>.78</td>
</tr>
<tr>
<td>Analogy x Diagram x Vz Interaction</td>
<td>.39</td>
<td>.46</td>
<td>.09</td>
<td>.86</td>
<td>.39</td>
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</tbody>
</table>
TABLE VI

*Reported Comprehension Strategy Use by Experimental Condition*

<table>
<thead>
<tr>
<th>Condition</th>
<th>Isolated</th>
<th>Parts</th>
<th>Interactions</th>
<th>No Effort</th>
</tr>
</thead>
<tbody>
<tr>
<td>Analogy Only</td>
<td>16</td>
<td>7</td>
<td>14</td>
<td>2</td>
</tr>
<tr>
<td>Diagram Only</td>
<td>16</td>
<td>9</td>
<td>14</td>
<td>1</td>
</tr>
<tr>
<td>Both</td>
<td>18</td>
<td>7</td>
<td>11</td>
<td>3</td>
</tr>
<tr>
<td>Plain Text</td>
<td>17</td>
<td>7</td>
<td>10</td>
<td>3</td>
</tr>
</tbody>
</table>
## TABLE VII

*Point Bi-Serial Correlations between strategy use and dependent measures and individual differences in spatial skills (visualization and reasoning).*

<table>
<thead>
<tr>
<th>Strategy Use</th>
<th>Concept</th>
<th>Connectedness</th>
<th>Multiple Choice</th>
<th>VZ</th>
<th>Reasoning</th>
</tr>
</thead>
<tbody>
<tr>
<td>Isolated</td>
<td>.32**</td>
<td>.32**</td>
<td>.29**</td>
<td>.17</td>
<td>.15</td>
</tr>
<tr>
<td>Parts</td>
<td>.18*</td>
<td>.11</td>
<td>.08</td>
<td>.05</td>
<td>-.01</td>
</tr>
<tr>
<td>Interactions</td>
<td>-.21*</td>
<td>-.15</td>
<td>-.09</td>
<td>-.18*</td>
<td>-.19*</td>
</tr>
<tr>
<td>No Effort</td>
<td>-.28**</td>
<td>-.26**</td>
<td>-.34**</td>
<td>-.16</td>
<td>-.10</td>
</tr>
</tbody>
</table>
Figure 1. Shown is individuals’ relationship between visualization skills and number of concepts included in essays split by analogy condition. Individuals who received an instructional analogy showed a weakened relationship between visualization skills and essay quality.
Figure 2. Shown is individuals’ relationship between visualization skills and number of concepts included in essays split by diagrammatic condition. There was no ATI between the presence of phase diagrams and the relationship between visualization skills and essay quality.
Figure 3. Shown is individuals’ relationship between visualization skills and multiple choice score split by analogy condition. Individuals who received an instructional analogy showed a weakened relationship between visualization skills and multiple choice score.
Figure 4. Shown is individuals’ relationship between visualization skills and multiple choice score split by diagrammatic condition. There was no ATI between the presence of phase diagrams and the relationship between visualization skills and multiple choice score.
Figure 5. Moderated mediation of the relationship between spatial visualization skills and multiple choice test scores, mediated by mental model quality as a function of the presence or absence of an analogy.

No Analogy Condition

- Mental Model Quality → .42***
- Spatial Visualization Skills → Mental Model Quality
- Mental Model Quality → .72***
- Mental Model Quality → Multiple Choice Test
- Spatial Visualization Skills → Multiple Choice Test
- Multiple Choice Test

(0.22*)

Analogy Condition

- Mental Model Quality → .63***
- Spatial Visualization Skills → Mental Model Quality
- Mental Model Quality → .62***
- Mental Model Quality → Multiple Choice Test
- Spatial Visualization Skills → Multiple Choice Test
- Multiple Choice Test

(0.06ns)
Figure 6. The number of concepts included in essays split by visualization skill, and experimental manipulations. Individuals with low visualization skills (left) had an increased number of concepts in their essays when they were provided with an instructional analogy. Individuals with high visualization skills (right) tended to show an increase in the number of concepts included in their essays when they were provided with only phase diagrams.
Approval Notice

Amendment to Research Protocol and Consent Documents – Expedited Review
UIC Amendment #12

May 24, 2012

Jennifer Wiley, PhD
Psychology
1054-D B.S.B., M/C 285
Chicago, IL 60612
Phone: (312) 355-2501 / Fax: (312) 413-4122

RE: Protocol # 2000-0676
“Understanding in Science: Eyetracking Studies”

Dear Dr. Wiley:

Members of Institutional Review Board (IRB) #2 have reviewed this amendment to your research and consent forms under expedited procedures for minor changes to previously approved research allowed by Federal regulations [45 CFR 46.110(b)(2)]. The amendment to your research was determined to be acceptable and may now be implemented.

Please note the following information about your approved amendment:

Amendment Approval Date: May 24, 2012

Amendment:
Summary: UIC Amendment #12 (response to modifications), submitted 22 May 2012, is an investigator-initiated amendment regarding the following: (1) adding surveys collecting participants' demographic information as well as prior concepts and knowledge related to various topics as part of future psychology department mass testing sessions; (2) increasing subject enrollment from 8,000 to 10,000 (revised Initial Review application; demographic data collection instruments); and, (3) submission of revised consent documents reflecting the above (Agreement to Participate in Research-5 PEC, version 9, 05/08/2012; Agreement to Participate in Research-1 PEC, version 9, 05/08/2012; Agreement to Participate in Research-1.5 PEC, version 9, 05/08/2012; Agreement to Participate in Research-2 PEC, version 9, 05/08/2012; Eyetracking No Bite Bar-1 PEC, version 2, 05/08/2012; Eyetracking No Bite Bar-1.5 PEC, version 2, 05/08/2012; Eyetracking No Bite Bar-2 PEC, version 2, 05/08/2012; Eyetracking-1 PEC, version 9, 05/08/2012).

Approved Subject Enrollment #: 10,000

Performance Sites: UIC

Phone: 312-996-1711
http://www.uic.edu/depts/ovcr/oprs/ FAX: 312-413-2929
Sponsor: Institute of Educational Sciences, Institute of Education Sciences

PAF#: 2007-02387, 2007-02387

Grant/Contract No: R305H030170, R30B07460

Grant/Contract Title: Improving Monitoring Accuracy From Scientific Text, Improving Metacomprehension and Self-regulated Learning from Scientific Texts

Informed Consents:

a) Agreement to Participate in Research Web Version .5 PEC; Version 9; 05/08/2012
b) Agreement to Participate in Research Web Version - 1 PEC; Version 9; 05/08/2012
c) Agreement to Participate in Research Web Version - 1.5 PEC; Version 9; 05/08/2012
d) Agreement to Participate in Research Web Version - 2 PEC; Version 9; 05/08/2012
e) Eyetracking No Bite Bar Version - 1 PEC; Version 2; 05/08/2012
f) Eyetracking No Bite Bar Version - 1.5 PEC; Version 2; 05/08/2012
g) Eyetracking No Bite Bar Version - 2 PEC; Version 2; 05/08/2012
h) Eyetracking - 1 PEC; Version 9; 05/08/2012

Please note the Review History of this submission:

<table>
<thead>
<tr>
<th>Receipt Date</th>
<th>Submission Type</th>
<th>Review Process</th>
<th>Review Date</th>
<th>Review Action</th>
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<tr>
<td>05/09/2012</td>
<td>Amendment</td>
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<tr>
<td>05/22/2012</td>
<td>Response To Modifications</td>
<td>Expedited</td>
<td>05/24/2012</td>
<td>Approved</td>
</tr>
</tbody>
</table>

Please be sure to:

➔ Use only the IRB-approved and stamped consent documents when enrolling subjects.

➔ Use your research protocol number (2000-0676) on any documents or correspondence with the IRB concerning your research protocol.

➔ Review and comply with all requirements on the enclosure, "UIC Investigator Responsibilities, Protection of Human Research Subjects"

Please note that the UIC IRB #2 has the right to ask further questions, seek additional information, or monitor the conduct of your research and the consent process.

Please be aware that if the scope of work in the grant/project changes, the protocol must be amended and approved by the UIC IRB before the initiation of the change.

We wish you the best as you conduct your research. If you have any questions or need further help, please contact the OPRS at (312) 996-1711 or me at (312) 996-2014. Please send any correspondence about this protocol to OPRS at 203 AOB, M/C 672.
Sincerely,

Sandra Costello
Assistant Director, IRB # 2
Office for the Protection of Research Subjects

Enclosures:

1. UIC Investigator Responsibilities, Protection of Human Research Subjects
2. Data Security Enclosure
3. Informed Consent Documents:
   a) Will be forwarded with Continuing Review approval letter

cc: Jon D. Kassel, Psychology, M/C 285
Andrew R. Taylor  
Department of Psychology  
University of Illinois at Chicago  
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Education:
B.S. in Psychology, Biomedical Sciences April, 2011, Grand Valley State University

Publications:

Manuscripts in Preparation:


Presentations:


**University Presentations:**


**Academic Related Experience:**
Graduate Teaching Assistant
Psychology 343: Statistical Methods, F14, Olga Goldenberg
Psychology 100: Introduction to Psychology, Sp13, Dr. Cheryl Cohen
Psychology 343: Statistical Methods, Sp13, Dr. Julie Chen
Psychology 343: Statistical Methods, F13, Dr. Maike Luhmann

Graduate Research Assistant, August 2011- December 2012
IES Funded Project: Reading for Understanding Across Grades 6 through 12:
Evidence-based Argumentation for Disciplinary Learning: Joint PIs Susan Goldman, Thomas Griffin, James Pellegrino, Jennifer Wiley

Undergraduate Mentoring:
Melissa Pasierb (Spring 12) Analogies and Learning
Stephanie Blakeslee (Spring 12) Analogies and Learning
*Sarah Davis (Fall 11, Spring 12, Summer 12, Fall 12) Learning from Multiple Documents
  *LASURI Award Winner, Hirschberg Research Grant and Best Paper Award Winner
Tegan Michl (Summer 12, Fall 12) Learning from Multiple Documents
Ishan Patel (Fall 12) Analogies and Learning
Saumil Thakkar (Fall 12) Analogies and Learning

Professional Membership and Service:
Student Member, Society for Text and Discourse
Student Member, Midwestern Psychological Association

Conference Reviewer, 22nd Annual Meeting of the Society for Text and Discourse,
Montreal, Canada, July 2012
Conference Reviewer, 23rd Annual Meeting of the Society for Text and Discourse,
Valencia, Spain, July 2013

Other Activities/Skills:
SPSS statistical software
R statistical software
SAS statistical software
Eprime 2.0
Experiment Builder
Full Microsoft Office Suite
HTML programming experience