The Effect of Two-Dimensional and Stereoscopic Presentation on Middle School Students' Performance of Spatial Cognition Tasks

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Abstract

Nineteen middle-school aged students visiting a planetarium were presented with three types of spatial cognition tasks using both two-dimensional (flat) and stereoscopic representations. The students' performance on tasks was evaluated in order to determine the impact of stereoscopic presentation upon accuracy and task completion time. Results show that accuracy did not differ between the two representational types while completion time was greater for the stereoscopic representations. Post task interviews show that students continued to think of the stereoscopic spatial tasks as two-dimensional. Results were analyzed through the lenses of cognitive load and cue theory.

Introduction

The real world is three-dimensional. Yet, inherent limitations of textbooks and computer screens require students to experience many scientific objects as two-dimensional (2D), i.e. “flat”. This can lead to student conceptions of three-dimensional (3D) objects based on inaccurate and oversimplified representations (Marr & Nishihara, 1978). For example, 2D interpretation of molecules can lead to misunderstandings of their true spatial structure (Copolo & Hounshell, 1995; Griffiths & Preston, 1992).

Some educators have attempted to use stereoscopic displays to overcome restrictions imposed by 2D representations. These displays add a sense of depth perception to the representations through the use of binocular vision. Our review of empirical studies on their effectiveness in the classroom found. positive (Holford, 1970; Drascic, 1991), null (Cliburn & Krantz 2008; Kim, et al., 1987), and mixed (Barfield & Rosenberg, 1995; Hansen, Barnett, McKinster, & Keating, 2004; Hsu, Pizlo, Babbs, Chelberg, & Delp, 1994; Reinhart, W. , Beaton, & Snyder, 1990; Trindade, 2002) results.

The research question addressed in this study is how do middle school students process spatial cognition tasks presented with two dimensional and stereoscopic representations? Student performance on spatial cognition tasks was measured with both the accuracy of their answers to the tasks and the mean amount of time needed for them to arrive at their answers. Analysis of post-session interviews was used to obtain strategies students applied to solve spatial tasks when working with both representational types.

The representations used in this study consist of drawings of letters and diagrams of real life 3D objects (specifically, pieces of folded paper and a NASA robotic rover). They are presented in a 2D manner (as printed on a piece of paper) and a stereoscopic manner (as seen through “3D glasses” with a stereoscopic projection system). Outside of the study materials, we use representations as a term referring to symbols, drawings and diagrams representing scientific objects.

This paper begins with literature review of previous work investigating 2D representations of 3D scientific objects in education along with an introduction to stereoscopic technology. To understand how 3D spatial information are processed and how much effort is needed to solve spatial tasks, we review cue theory and cognitive load theory. The study methods are presented, followed by description of the analysis of spatial cognition task results and post-interview transcripts. Finally, implications for the use of stereoscopic technology in the classroom are discussed.

The Challenge of Understanding 3D Objects Through 2D Representations

Two-dimensional and 3D representations of the same three-dimensional object can be very different. Figure 1 includes both a 2D drawing of a simple house and a 3D drawing of the same house. Note the addition of multiple sides of the house and how it makes it look much larger. 2D representations often show one side of a three dimensional object, usually with a field of view aligned with a 90 degree axis through the center of the object. A typical 3D presentation uses 2D space but shows the third dimension by showing select portions of multiple sides, adding cues to provide a sense of depth and often providing a manipulative viewpoint (such as in interactive modeling programs).

Insert Figure I Here

There are many ways of presenting spatial concepts, but most involve 2D presentations on paper, a computer screen or, more recently, in virtual environments (Dede, Salzman, Loftin, &

Sprague, 1999). Yet, most scientific objects are 3D in nature. Depicting these concepts on flat surfaces, such as textbooks or video screen, is a challenge due to limitations imposed by a flat surface (Hubona*,* Shirah, & Brandt, 1999). The same challenge applies to when students read textbooks and must create a mental image of a real, 3D object based on a 2D representation of the object. Most current learning materials require students to do just that. Referring to an astronomy textbook's portrayal of spatial scale, Barab, Hay, & Duffy (2000b) quoted one student saying, "This picture is wrong, there is no way they could get Mercury, Earth and Saturn all in the same picture. The distances are too great.... My science book lied," (p. 10).

Why did the student feel frustrated by the textbook? Some concepts, such as the 3D spatial arrangement of planetary orbits, may be too difficult for some students to understand based on 2D representations alone (Barab, et al., 2000b; Gotwals, 1995; Hansen, 2004). For example, three dimensions are needed to show that Pluto's orbit is both more elliptical than other planets and also in a different plane. Also, such 2D representations may be poorly designed, causing students' imagination to fill in the blanks with previously built-in assumptions based on their experience in the world (Wanger, Ferwerda & Greenberg, 1992). Research has shown such translation is especially difficult in the domains of astronomy (Parker & Heywood, 1998; Keating, Barnett, Barab, & Hay, 2004) and chemistry (Wu & Cheng, 2007; Wu & Shaw, 2004), two highly spatial fields of science.

Cue Theory: How 2D Information Can Be Translated into 3D Imagery

3D representations are most successful when incorporating elements from cue theory. The core tenet of cue theory is that depth perception comes from the posture of the eyes and from patterns of light projected onto the eyes from the environment (Wanger, Ferwerda & Greenberg, 1992). What constitutes a cue is debated within the field (see Landey, Maloney, Johnston & Young [1995] for a review). In general, cues are divided into two categories: *primary* and *pictorial*. Primary cues involve physiological responses (such as the stereo effect of wearing 3D glasses) and pictorial cues involve cues built into artificial representations (such as drawing closer objects larger than objects further away).

Studies have shown that the processing of depth cues is the most challenging component of 3D representations (Tuckey, Selvaratnam & Bradley, 1991). Seddon and Eniaiyeju (1986) and Hu, Gooch, Creem-Regehr, and Thompson (2002) found that depth cues work best when multiple cues are used in tandem. The importance of this relationship is because depth cues provide distance information relative to each other, but not absolute (relative to outside cues) (Kim, Ellis, Tyler, Hannaford, & Stark, 1987; Willemsen, Gooch, Thompson, & Creem-Regehr, 2008) thus the relationship between cues is very important in a representation.

Two specific types of pictorial cues have had success in bridging the barriers between 2D and 3D thinking: shadows and reference frames. Shadow cues are placement of shadows on an object based opposite of the location of a light source. It has been successfully used in many 3D learning tasks (Hu, et al. 2002; Hubona, Wheeler, Shaw & Brandt, 1999; Wanger, Ferwerda & Greenberg, 1992;). However, Shubbar (1990) found that shadows used alone had no effect on student understanding of molecular diagrams.

Reference frames can also serve as successful depth cues in 3D representations (Wickens, Vinkow & Yeh, 2005). A reference frame is generally defined as how locations are expressed within space (Klatzky, 1998). In this paper, a reference frame refers to spatial *context* in which an image element is placed within the overall representation. Only a single reference frame can exist simultaneously in 2D representations, however 3D representations can have multiple reference frames at the same time, which add to their complexity. The importance of reference frames can be illustrated by considering how different the spatial size of the Moon appears when it is directly overhead vs. when it is just above the horizon (Wanger, Ferwerda,& Greenberg, 1992). Without a reference frame, the Moon looks much smaller when overhead leading to a major misconception in astronomy (Galili, Weizman & Cohen, 2004). Translation from 2D to 3D reference frames requires a special type of mental rotation which is qualitatively different than of lateral rotation (ex: relating the horizontal movement of a computer mouse with the vertical movement of its cursor) (Wickens, Vinkow & Yeh, 2005). This translation becomes easier when the reference frames being rotated are aligned with the observer's body (Tarr & Pinker, 1990) or along other axes with which humans are familiar (Tversky, 2005). Together, the use of shadow and reference frames can act as effective pictorial cues that help the viewer translate information from a 2D representation to 3D thinking of a 3D object.

Stereoscopy as a Primary, Physiological Depth Cue

Stereoscopy is a technique of showing different images to the right and left eyes, creating a sense of depth (Wheatstone, 1858). Most people are familiar with the concept through the wearing of 3D glasses at a movie theatre or science museum. Children, in particular, have a propensity for stereoscopic technology. Stereoscopic video games are currently being designed for all the major video game platforms (Warren, 2008) and 3D television sets are about to be released at the consumer market (Tieman, 2008). Most major movie theater chains are installing stereoscopic equipment (Gonsalves, 2008) because all future movies by Disney's Pixar division (Pixar, 2008) and the Dreamworks movie studio (Khatau, 2008) will be released in 3D.

Most stereoscopic learning studies focused on problems with 2D representations which, by their nature, seemed to be suited to stereoscopy. For example, people tend to underestimate the distance to objects in 2D virtual environments (a phenomenon known as compression) (Creem-Regehr, Willemsen, Gooch, & Thompson, 2005). The use of stereoscopic images helped in determining more accurate distance to objects and limiting the effects of compression (Barfield & Rosenberg, 1995). It should be noted that it did not help in determining angles in the representation. Cole, Merrit, Fore & Lester (1990) found that stereoscopic representations made remote manipulation of a robotic extension through a maze easier than a system of 2D representations. Ware & Franck (1996) found that the amount of data understood in a graphical display increased by 60% when displayed stereoscopically. Wickens, Merwin & Lin, (1994) found that stereoscopy increased understanding of large scale structure of stereoscopic visualization of large scale data sets, but had no effect on understanding of details in the data. And, unlike pictorial depth cues, stereoscopy has been shown to be effective when used *without* other cues (Kim, et al., 1987; Yeh & Silverstein, 1992) because it is accurate regardless of the distance or viewing angle (Surdick, Davis, King, & Hodges, 1997). Also, stereoscopic depth cues can be learned quicker than pictorial depth cues (Drascic, 1991).

Stereoscopy studies in educational settings have reported positive (Holford, 1970; Drascic, 1991), null (Cliburn & Krantz 2008; Kim, et al., 1987), and mixed (Barfield & Rosenberg, 1995; Hansen, Barnett, McKinster, & Keating, 2004; Hsu, Pizlo, Babbs, Chelberg, & Delp, 1994; Reinhart, Beaton, & Snyder, 1990; Trindade, 2002) results. The one apparent common theme among the positive stereoscopic results is its use with highly spatial concepts. When tested on a number of chemical and physical topics, Trindade (2002) found that stereoscopic visualizations increased understanding in only one of the topics: phase transitions of elements. In an object identification task, stereoscopic displays enhanced learning of the physical arrangements of objects in 3D space but did not enhance understanding of other physical characteristics of the objects (Hsu, et al., 1994).

The historically high cost and complexity of stereoscopic display systems have kept them from being used in large numbers. However, accessibility is becoming less of an issue. One of the first stereoscopic displays produced en masse was the CAVE (CAVE Automatic Virtual Environment) (Cruz-Neira, Sandin & DeFanti, 1993). CAVE is the prototype for a fully immersive VR system. The system was admittedly very complex and costly, had trouble with showing accurate colors and generally was not robust enough for public use. However, it was more affordable than other systems of the time and it was widely adopted in settings where science visualization was important, such as research laboratories. Variants of CAVE are still in use today (Ohno, Kageyama & Kusano, 2006).

This study used a descendent of the CAVE, referred to as the GeoWall. It consists of off-the-shelf components and open-source software to project a stereoscopic image that can be easily viewed by many people in a small room. A complete GeoWall system is affordable and portable enough to be transported between schools and classrooms. GeoWalls have been installed at over 400 locations, mostly at universities and museums (Morin, 2004). The U. S. Geological Survey adopted the system in 2000 for use in education and public outreach projects (Steinwand, Davis & Weeks, 2002). GeoWall systems are being developed to teach chaos theory, fractal geometry and mathematical physics (Abraham, Miller & Miller, 2005), architecture (Kalisperis, Otto, Muramoto, Gundrum, Masters, et al., 2003) and engineering (Messner & Horman, 2003). None of these particular GeoWall applications have been empirically studied for their effect on learning.

Cognitive Load Theory: Cognitive Effort in Processing Spatial Information

A common worry is that stereoscopic environments require too much mental work from the viewers and can overload their senses leading to cognitive overload and mental fatigue (Dede, et al., 1999; Okuyama, 1999). According to cognitive load theory, efficient use of working memory leads to better retention in the long-term memory (Sweller, 1988). There is a limited amount of short-term memory, which is structured into separate modalities (such as auditory and visuospatial) that feed into unlimited long-term memory.

Stereoscopic displays may reduce cognitive load by limiting the functions the mind may need to perform when converting between 2D and 3D representations (such as interpreting depth cues and coding the location of reference points). Pepper, Smith, & Cole (1981) found an advantage of stereoscopic displays over traditional displays, which increased as the screen quality degraded or became more cluttered. Kim et al. (1993) suggest this may be especially true if the target task is much simpler than the environment in which it is presented. On the other hand, stereoscopic displays have also been reported to increase cognitive load due to visual fatigue (Kooi & Toet, 2004).

Stereoscopy has been used for decades for pilot training as a tool to increase spatial awareness while not increasing cognitive load (Nataupsky & Crittenden, 1988; Parrish, Busquets, & Williams, 1990). In immersive environments, such as professional flight simulators, many events are happening at once and the trainee is bombarded with data from many different sources and directions. One of the sources of data is flat computer monitors representing the windows on a real airplane. The pilot's working memory should be focused on the steps needed to pilot the aircraft and not on steps needed to translate graphical representations on monitors. By making the monitors stereoscopic, the pilot may not have to do as much 2D to 3D translation, thus freeing working memory. This is how we think cognitive load theory may apply to learning in stereoscopic environments.

According to Paas, Tuovinen, Tabbers, & Van Gerven (2003), cognitive load can be measured through three properties: *mental load, mental effort,* and *performance*. Mental load is imposed by the task and environment demands and mental effort is the amount of resources allocated to the task (Paas & Van Merriënboer, 1994). Mental load and mental effort are difficult to measure outside of a laboratory setting since they involve the use of secondary tasks. Performance, on the other hand, can be measured in terms of item accuracy and time on task (Pass, et al., 2003) – two measures available in active learning environments. By measuring performance, it is possible to examine how cognitive load changes when the mind is processing a 2D or a stereoscopic task while in a learning environment.

Cognitive load theory can be beneficial to studying the differences between how students process 2D and 3D spatial information because it can be used to probe the level of mental processing involved in the tasks. Differences in cognitive load can be a sign that students are processing the two forms of information differently.

Method

This study compares student performances on spatial tasks when objects were presented using 2D and stereoscopic representations. For the purposes of this paper, 2D presentation refers to presenting spatial tasks on a piece of paper. Stereoscopic presentation refers to objects presented using a GeoWall system.

Data were collected in three steps. First, a brief demographic questionnaire was used to record age, gender, and prior experience with stereoscopic displays along with attitudes towards stereoscopic displays and the use of technology in the classroom. Second, cognitive load was measured using a series of spatial cognition tasks chosen from three previously published spatial cognition instruments: a letter rotation task (Shah & Miyake, 1996), a block rotation task (Bodner & Guay, 1997), and a paper folding task (Ekstrom, et al. 1976). These tasks were shown first in a flat, 2D format and then stereoscopically. They were chosen because they reflect increasing degrees of difficulty in terms of 3D operations. For this study, we define 3D operations as mental manipulation of a representation that involves the z-axis (a.k.a. “in and out” or “front and back”). While the letter rotation task involves no z-axis manipulation, the block rotation task involves a single z-axis manipulation and the paper folding task involves multiple z-axis manipulations. These are tasks that have previously been used in spatial cognition studies. While they were presented in an authentic learning environment, they are not learning tasks per se. Therefore, this study does not evaluate the learning potential of stereoscopic presentations as compared to 2D presentations. Finally, 5 minute post- interviews were conducted to examine how respondents approached each task and which presentation format they preferred. In these interviews, students’ responses to the spatial cognition tasks in both presentation formats were used.

Spatial Cognition Tasks

The letter rotation tasks involved spatial ability associated with only 2D visualizations. The block rotation tasks required one mental manipulation of a 3D object. The paper folding tasks required multiple manipulations of a 3D object.

Task 1: letter rotation tasks. The letter rotation task was originally developed to assess spatial ability without involving verbal ability. On a piece of paper, a letter was written either normally, or reversed (as seen through a mirror) (Figure 2). It was also rotated so that the top was pointed at one of four numbered angles. The goal of the task was to state from memory whether the letter was normal or backward as well as at which angle it was pointed. After a short practice, a total of three sets were used successively. The first set had only two letters. The next set had three letters. And the last set included four letters. After each set, the student was given an answer sheet to record the perspective (normal or backward) and pointing direction of the letters. Presumablely, the difficulty of the sets increased as more memory was needed to process the increasing number of letters in each set. The stereoscopic version of the letter rotation tasks displayed the letters through the GeoWall instead of on a piece of paper. The rest of the procedure was the same. The same letters, orientations, number of items and sets were used. However, the order of items within each set was different between the paper and stereoscopic presentations.

Figure 2 placed here.

Task 2: block rotation task. The second task was modeled on an exercise from the Purdue Visualizations of Rotation Test. In the original task, the image of a 3D modeled block is shown before and after it has been rotated. Then another block is shown with four choices, one of which shows how the new block would look after it was rotated similarly to the original block. The student has to identify that block from four choices. In this study, the original block was replaced with a 3D model of the NASA rovers currently exploring Mars. See Figure 3. After one practice rotation task, four rotation tasks were used. For the stereoscopic version, the before and after representations of the rovers were displayed in separate pairs via the GeoWall. So it appeared as if the rovers “came out” of the wall, toward the student wearing the glasses. Using a controller, the student could flip back and forth between the images as needed. The rest of the procedure involved the same types of rotations (but the ordering of the answer choices was changed), items, sets, and answer sheets.

Figure 3 placed here.

Task 3: paper folding task. The third task was modeled on the classic mental paper folding exercise. Diagrams of a piece of paper being folded and then having a hole punched in it were shown (Figure 4). Then, four diagrams of the unfolded piece of paper were shown beneath it, with one of them showing how the paper will correctly look when unfolded after the hole punch. The session began with one practice task followed by four tasks of increasing complexity. The first task involved two paper folds and the last task involved five folds. For the stereoscopic version, the 2D diagrams were replaced with a 3D rectangle shown with a surface texture rendered to look like a piece of paper. The 3D “paper” was designed to have pieces of the paper look like they are “coming out” from the screen while the rest appeared flat. Where those two pieces connected was the fold point on the paper. The dotted lines on the 2D diagrams were used as the angles at which the stereoscopic paper was folded. Only one fold could be seen at a time. The other folds could be viewed by using a controller to move forward and backward as many times as needed. The same number and types of folds were used as in the 2D version with a different order of answer choices.

Figure 4 placed here.

Subjects

This study was conducted over a seven-day period at a planetarium and astronomy museum in a large Midwestern city in the United States. Nineteen middle school students (*M* = 11.8 years, *SD*

= 1.7 years) were randomly selected from among visitors at the museum. Ten students were female and nine male. All but one student had prior experience watching 3D movies. Most students in this study were avid computer users - about 56% of the students played video games at least once per week. About 89% used computers at least monthly in class. When asked if they were “not at all”, “somewhat” or “very much” interested in using computers for learning”, no students chose “not at all” and 63% chose “very much”.

Procedure

Each session took place in the Space Visualization Laboratory (SVL). The SVL is a room on the museum floor open to the public for limited hours. The room is separated from the rest of the museum floor by transparent glass walls. Five interactive science visualization exhibits are located around the room. In the middle of the room is a closet housing the GeoWall system that projects stereoscopic images onto a large screen mounted on a wall (Figure 5). The sessions took place at a desk about 300-450cm from the stereoscopic display screen. Previous studies show variations in how people perceive stereoscopic representations that are in physically close proximity to their eyes (~25cm), but no effects out to their tested limit of 405cm. (Bradshaw & Glennerster, 2005). Sessions took about 12-20 minutes for each student.

Figure 5 placed here.

At the start of the session, the student answered a set of demographic questions. Then they completed the 2D letter rotation, paper folding and block rotation tasks by recording their answers on provided answer sheets. Next, they were introduced to the GeoWall. They put on the polarized glasses and went through the stereoscopic versions of the same tasks as on paper. They looked at the screen for the representations and then chose an answer from choices on answer sheets which were identical to the 2D tasks, except in the order of their choices. In one session, a technical problem prevented the GeoWall from functioning properly so data from the stereoscopic tasks for that session were omitted from our analysis, resulting in a total of 18 students completing all three types of spatial tasks on paper and the Geowall. The time was recorded for each type of tasks from when they began the first item to when they finished answering the last item for the task. Therefore, a total of six times were recorded (3 task types x 2 presentation types). At the end of the session the students were asked about how they solved each of the three tasks. They were also asked whether they preferred the 2D or stereoscopic presentations. Audio was recorded during the entire session, including the interview. Written field notes were also recorded when the students did something out of the ordinary during the session and also to serve as a back up to the recording of the interviews. The interviews averaged approximately three minutes in length and consisted of variations of the following two questions, asked of each task:

- *(holds up a sample answer sheet from each of the task types):* Can you tell me when you were solving this problem, what was the strategy you used? In general, what did you do in your mind?
- Did you prefer to answer this question on paper or via the 3D wall?'

Data Analysis

Two outcome variables were obtained on each of the three task types: response accuracy and time on task. For the response accuracy variable, each of the tasks were scored as a 0 for an incorrect answer or 1 for a correct answer. For the letter rotation tasks, separate scores for perspective (backward or normal) and orientation (which direction the letter was pointed) were recorded. All scores were then converted to a ratio by dividing the correct answers by the maximum numbers of task items to provide a value with a range of 0 and 1. Thus, higher numbers mean higher accuracy. Time on task was measured as the difference in seconds between the start and the end of the task type. It was not further processed. Both accuracy ratio and time on task variables represent student performance on the three spatial tasks presented in 2D and stereoscopic presentation formats. This means that each student had six entries in both variables. In order to indicate how each of six entries connected to which student, which presentation type, and which spatial task, three additional variables were created. For the student variable, each student was assigned a number from 1 to 19. The presentation type variable includes “1” for 2D and “2” for stereoscopic presentation. The spatial cognition task variable was represented as a number: “1” for the letter rotation task, “2” for the block rotation task and “3” for the paper folding task.

We then applied mixed effects ANOVA's to the two outcome variables on accuracy and time. The independent variables were presentation type (2D vs. stereoscopic) and spatial task (letter rotation vs. paper folding vs. block rotation). The student variable was considered as random effects.

The post-session interviews were transcribed and analyzed for insight into how the students solved the various tasks. In some cases, the audio of the entire testing session was reviewed for evidence to support or contrast statements made by the students in the post-session interviews. The interviews were analyzed by looking for patterns between the students' responses and by looking for mention of anything that could be related to depth cues (such as talking about shadows). In particular, we looked for differences in how they described the processing of the 2D and stereoscopic tasks which may shed light on any differences in performance.

Results

The first two subsections describe results on two outcome variables: accuracy and time on task. The third subsection describes how the interviews were analyzed to look for reasons behind the outcome variable results.

Accuracy

Table 1 shows the mean value for each task categorized by presentation type. As shown in Table 2, the mixed effects ANOVA results indicate no statistically significant main effect of presentation type on accuracy performance or task type. The lack of difference in performance accuracies means that using a stereoscopic environment neither enhanced nor hindered the students' ability to successfully answer the task items when given enough time.

There is a statistically significant interaction effect between student and task type. However, the main student effect and the student/presentation type interaction are not significant. This means that all students' performances were similar between presentations. Some students performed better on some tasks than others, as opposed to students performing equally on all tasks.

Tables 1 & 2 placed here.

Time on Task

A mixed effects ANOVA indicate a significant main effect of presentation format, Stereoscopic visualizations required more time than 2D presentations. As shown in Table 3, significant differences in time on task were also found for the type of task, indicating students took more time to solve spatial cognition tasks that require more 3D operations. The time required to solve the letter rotation task in the stereoscopic environment *decreased* compared to the 2D representational environment (Table 3). However, there was a modest *increase* in time required to complete the block rotation task from the letter rotation task and a *larger increase* in the time required to complete the paper folding task. There is a significant interaction effect between student and task type, which is also found with accuracy, as described earlier.

Tables 3 & 4 placed here.

The letter rotation task is inherently a 2D task – the letters appear flat even when projected stereoscopically. So the 2D and stereoscopic versions of the task are essentially the same. Thus, the decrease in completion time for the letter rotation task can be attributed to familiarity with the task, since the task had been previously presented on paper. However, the other two tasks appear differently when presented in 2D or stereoscopically. In the block rotation task, both the 2D and stereoscopic versions had pictorial depth cues. But only the stereoscopic version also included a primary depth cue, binocular vision. Thus the increase in completion time for this task, even though the student was already familiar with it, is likely due to the existence of primary cues related to stereoscopy that did not exist in the 2D version. The paper-folding task also appears much differently via a stereoscopic system, but with two added complications. First, it requires multiple rotations at the same time. Secondly, it had no pictorial depth cues at all – only the primary cue inherent in stereoscopy (binocular vision). This task had the largest increase in completion time between the 2D and stereoscopic versions. These results are supported by evidence that cues work best in combination. Thus, the increase in completion time caused by the stereoscopic environment can be related to the amount of 3D manipulations demanded by the task and by the presence, or lack thereof, of the primary and pictorial depth cues.

Note there was no increase in accuracy in the stereoscopic tasks, despite familiarity with the tasks. This could also be a sign that students are focused so much on the visiospatial processing that they are not deeply concentrating in the cognitive aspects of the tasks.

Table 5 placed here.

Post-Session Interviews

An analysis of interview transcripts provided some insight into the increase in time on task for the stereoscopic task results. Nothing out of the ordinary was found in their description of solving any of the 2D tasks. However, we noticed two important patterns in the language the students' used to describe how they solved the stereoscopic versions of the tasks: the consistent use of two-dimensional language and the usage of props.

When describing their problem solving methods for the stereoscopic tasks, they often used terms that reflect a continued 2D interpretation of the task, despite the fact that they were in a stereoscopic format and 3D operations were required to successfully complete the task. For example, three students used the term "flipped" a total of ten times when describing how they solved the tasks. After the interviewer asked one student to explain how they solved the paper folding task, the student said:

> Student 1: I did the same thing, I had this square and if it was, say, flipped over and it had to be slanted first then it had to be flipped over, then I looked at the square and I noticed the shapes on it and if it wasn't the same shapes then it would be flipped over.

This 2D thinking was manifested in oversimplified analysis of the rotations to which they were exposed. The letter rotation items were rotated only at angles of 45, 135, 225 or 315 degrees. And the block rotation items were always rotated at an odd angle that included all three-dimensions (x, y, and z). That is, these two tasks were *never* simply flipped one way or turned upside down. Yet, students still referred to them in that manner by using terms such as “upside down”, “backward”, “forward” and “normal” (as a synonym for “forward”) to describe their mental rotation process, with no additional explanation. The following are examples of interview responses. They were chosen as a representative sample of the types of responses in the interviews.

Interviewer: Can you tell me when you were solving this problem, what was the strategy you used? In general, what did you do in your mind?

Student 12: I put them back in (unintelligible) to see if they were forward or backward.

Interviewer: And, what about the rovers. Can you tell me how you did that one?

Student 12: Hmm, I tried to move the block the way it was flipped.

Interviewer: Can you describe me your strategy for solving this one in your mind and how you did it?

Student 11: Well, let’s say there is, like, all of them there, and I, basically, if there was, like, 4 of them and if one of them could have been normal or backwards then normal or backwards then I would just try to remember that and then really all of them they didn't really all go into the same exact area...

Interviewer: Can you tell me when you were solving this letter question, how did you solve it? What was your strategy?

Student 13: I just thought it was like it was supposed to be forward or backward like that.

Interviewer: For these letter problems, can you describe to me what your strategy was to solve them?

Student 22: First of all, I looked at, um, the number so if it would be four then I looked at it four, then looked backward so I remembered it as four backwards.

Not all interviews had responses that showed two-dimensional thinking when describing 3D operations. However, this was the only pattern found.

Beyond the 2D language used by students to explain their thinking, they also used props to help solve the stereoscopic tasks. However, they did not use them for the 2-D tasks. Speaking of the stereoscopic block rotation task, one student used their hand to illustrate their point while saying, "I just rotated my hand the way and compared it with [the screen] to see what it would look like." Another student said the paper folding task was easier on paper, "...because I had the paper in front of me, so I could imagine it." Inspection of field notes show that a total of four students (including the two quoted previously) used their hands or paper to help solve the stereoscopic problems, yet there is no evidence in the transcripts or field notes of any props being used by any student for the 2-D tasks. The students perceived the need to use props in the stereoscopic tasks while they did not feel the need to use them in the 2-D tasks, suggesting an awareness of the increased cognitive demands of stereoscopic problem solving. However, use of props were not related to 3D operations of the tasks, rather it was only related to the stereoscopic representations. This supports the use of physical manipulation as a crutch for problem solving in stereoscopic environments (Dori and Barak, 2001).

Discussion

This study shows that middle school students found stereoscopic representations more difficult to mentally manipulate than 2D images. The interviews suggest they visualize the stereoscopic images as flat representations and did not utilize depth cues. There is no difference in accuracy between their responses to 2D and stereoscopic tasks. However, students took significantly more time to choose an answer with the stereoscopic tasks, with the difference relating to the increasing demand for 3D operations in the tasks. The 2D to 3D mental translation needed to solve these tasks was not helped by the stereoscopic format. Stereoscopy, in fact, hindered the problem solving process when multiple 3D manipulations were required.

The increasing demand on cognitive resources could be caused by the extra steps needed to take a stereoscopic representation, mentally convert it to 2D and then perform a 3D operation on it. Students may do this because they have been effectively trained to think of representations as two-dimensional due to all the 2D representations that they are exposed to everyday. The extra step of converting a stereoscopic representation to two dimensions must be at least equally as difficult as performing a 3D operation on a 2D mental representation. The student would have to mentally manipulate at least two dimensions separately and then combine the results in their mind. This would explain the additional time it took to complete the tasks, the use of two dimensional language to describe their thought process and also why the there was no effect, positive or negative, on the accuracy results. Alternatively, another explanation could be that the stereoscopic representations are being viewed as visual items, not as representations. A study by Zacks, J., Levy, E., Tversky, B. and Schiano, D. J. (1998) showed a similar time delay in the processing of 3D graphs vs. 2D graphs. Those results, along with other data in their study, are interpreted as a sign that the 3D objects were being seen as visual items not related to a real world item. They suggest making the 3D objects more realistic because closer comparison "…to real-world objects may confer some advantages" (p. 135). Our time delay could be a signal that the brain is switching from a real-world mode to a simulated-world.

While this study did involve practice time, it was limited to a few practice items for each task. In most cases, the students did not even want to bother doing practice items in the stereoscopic format. They often made comments during practice such as "Yes, I know" and routinely would cut off explanation of the practice item and how to use the stereoscopic environment. In a few cases with older students, we experienced eye rolling as if this was too easy for them. In a learning environment, a possible solution is to make the practice sessions longer and more interesting by beginning the stereoscopic session by showing aspects of the learning curriculum that do not require 3D operations, but are nevertheless shown stereoscopically. That way they have a natural bridge of time from the 2D world of the textbook to the stereoscopic representations.

The students in this study were chosen from visitors to a planetarium in an urban environment in a large, Midwestern city during a time when most schools were closed for winter vacation. As a result, the population may be skewed towards urban families that find enjoyment in, or place a level of educational importance on, visiting science museums. However, we think the prior computer and 3D experience of students in this study is approximately equal to that of the general population. About 56% of the students in this study played video games at least once per week, which is in line with statistics showing that half of all children in American have a video game system in their bedroom (Roberts, 2000; Sherman, 1996 cited by Williams, 2006). About 89% of students in this study used computers at least monthly in class, which is in line with statistics showing that approximately 84% of K-12 classrooms had at least one computer available to students in 2000-2001 (Norris, Sullivan, Poirot & Soloway, 2003), a number that has likely increased since then. All students but one had prior experience in a stereoscopic environment, which is not surprising considering the proliferation of stereoscopic films these days.

The study is limited by a relatively small sample size. The small size is a function of the session time and the limited availability of the laboratory during the hours the museum is open to the public. Since the study took place in an active room of the museum, there were certain times when the room was needed for public events. Also, since compensation consisted of free family admission to the museum, sessions could not be conducted towards the end of the day. This effectively limited the availability of the lab to about four hours a day. Finally, even though each session only took 12-20 minutes to complete, it took considerable amount of time to recruit a family, get them admitted to the museum, help them place winter clothing in lockers and then walk them to the room. Larger than desired error bars in the statistics are one result of the sample size. It is possible that the difference in accuracy between the two presentation formats on the paper folding task could become statistically significant with a larger sample size. However, we feel the small sample size affects the qualitative data the most. Most students provided limited responses to our questions, thus the data was disproportionately limited by sample size, compared to the statistical results. More qualitative data would allow us to search for more patterns in the responses and provide a more thorough interpretation of the results.

It is important to note that this study was conducted in a laboratory setting with primarily cognitive tasks. Therefore, the results of this study cannot be generalized to real-world learning tasks that involve more than just spatially manipulating objects and, as such, cannot be compared with previous studies using stereoscopic representations in educational settings. More demands are placed on cognitive processes in an educational setting which makes it more difficult to separate mental visualization from other cognitive demands. These other demands may have interaction effects with the mental visualizations, for better or for worse. Our follow up research will be centered on a learning task to look for those types of interactions and also to test the use of multiple depth cues. It will involve the distribution of galaxies and its relationship to the size and shape of the Universe. Multiple depth cues and other established interactive design principles (Kali, 2006; Mayer, 2005) will be developed into the visualization along with more authentic techniques for assessing cognition load and learning results.

Conclusions, Implications and Future Research

The link between representations and learning is perception. In science classrooms, 2D perception of 3D objects is often the bottleneck in the learning process. Stereoscopy has been used for decades with some success to enhance perception by allowing the use of more sophisticated representations in textbooks (Holford, 1970).

The design of the tasks in this study, being taken from spatial cognition batteries, did not take into account representational design principles that are proven to lower cognitive load, such as the use of multiple representations, animation and verbal cues (Cook, 2006). Designers of stereoscopic representations should attempt to reduce the cognitive load needed to process the images. They may want to incorporate at least one pictorial depth cue into their representations instead of relying solely on the primary stereoscopic cue (Tory, Kirkpatrick, Atkins and Möller, 2006). Additionally, Mayer's multimedia learning principles have been successful in reducing cognitive load of 2D representations (Mayer, 2005) and may be similarly applied to stereoscopic representations. In our study, the lack of implementation of these principles may have overcome any possible advantage that the stereoscopic environment may have afforded.

In order to successfully use stereoscopic representations in a learning environment such as a classroom or a museum setting, students will also have to overcome their natural tendency to think of representations in strictly two dimensions. One possible way would be to design a pre-session training program that teaches students to trust what they see (such as having them navigate a stereoscopic virtual environment) (Dixon, 1997). Another possible way would be to incorporate cue theory, specifically multiple depth cues, into the representations since students are familiar with seeing them in modern computer applications. Studies have shown that 2D representations are often effective for tasks that require attention to detail while 3D representations are effective for tasks that require overall, generalized attention (St. John, Cowen, Smallman & Oonk, 2001). This may be true for stereoscopy as well, suggesting that it could be used for the beginning of a highly spatial learning task but not necessarily needed for the end of the task, when more detailed information is usually presented. This may explain the increasing time it took to process the tasks with more 3D operations, since they included more detail.

Our results are in line with previous studies indicating that depth cues work best when multiple depth cues are present at the same time (Kim, et al., 1987; Hu, et al., 2002; Seddon & Eniaiyeju, 1986; Tory, Kirkpatrick, Atkins and Möller, 2006; Willemsen, et al., 2008). The results conflict somewhat with those of Kim, et al., (1987) which reported increased stereoscopic performance on spatial tasks with no additional visual cues (depth or otherwise) present. However, their study showed that additional visual cues were still useful because they increased performance over tasks that had stereoscopic cues alone. Additional depth cues may act as a bridge between 2D and 3D thinking because students are used to seeing depth cues in 2D environments. Thus they offer something familiar to the student. Also, when a student sees depth cues they, by their very nature, think of the representation in multiple dimensions. So depth cues may also prime the students by preparing them for 3D thought.

As stereoscopic technology becomes simpler, more affordable and popular, there will be a temptation to blindly deploy it in classrooms. Results of this study show that this could be detrimental to the learning process if the added cognitive load to manipulate the three dimensional objects is not taken into account.

Stereoscopic displays are very popular with students. Stereoscopic video games are available for all the major video game platforms, 3D television sets are about to be released to the consumer market and national movie theater chains are installing stereoscopic equipment. Stereoscopic technology can bring this enthusiasm into the science classroom. However, our study shows that this could actually slow cognition when used with 3D objects and without consideration of other design principles. These results could have implications for instructional designers and educators who work in highly spatial learning domains such as astronomy, biology, chemistry, geosciences and physics. Specifically, educators and designers need to work further to determine how to take advantage of the fact that stereoscopic representations of spatial tasks require a different type of thinking than traditional, 2D representations. This may offer a way to assist students who have trouble with traditional, 2D representations of highly spatial concepts.

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References

Abraham, R., Miller, M., & Miller, J. (2005). Emerging 4D graphics for math and science education. Proceedings of International Conference on Computer Graphics and Interactive Techniques, 22. Retrieved November 9, 2007, from http://portal.acm.org/citation.cfm ?id=1187386

Barab, S. A., Hay, K. E., Barnett, M., & Keating, T. (2000). Virtual Solar System Project: Building Understanding through Model Building. *Journal of Research in Science Teaching*, 27, 719-756.

Barab, S. A., Hay, K. E., & Duffy, T. M. (2000). Grounded constructions and how technology can help. *CRLT Technical Report No. 12-00.*

Barfield, W., and Rosenberg, C. (1995). Judgements of azimuth and elevation as a function of monoscopic and binocular depth cues using a perspective display. *Human Factors*, 37, 173-181.

Bodner, G. M., & Guay, R. B. (1997). The purdue visualization of rotations test. *The Chemical Educator*, 2, 1-17.

Bradshaw, M. F. & Glennerster, A. (2005). Stereoscopic acuity and observation distance. *Spatial Vision*, 19, 21-36.

Cliburn, D., & Krantz, J. (2008). Towards an effective low-cost virtual reality display system for education. *Journal of Computing Sciences in Colleges,* 23, 147-153.

Cole, R. E., Merritt, J. O., Fore, S., Lester, P. (1990) Remote-manipulator tasks impossible without stereo TV. In Merrit, J. O. & Fisher, J. O. (Eds.) *Proceedings of SPIE Volume 1256 – Stereoscopic Displays and Applications* (pp. 255-265). Santa Clara: The International Society for Optical Engineering.

Copolo, C. F., & Hounshell, P. B. (1995). Using 3D models to teach molecular structures in high school chemistry. *Journal of Science Education and Technology,* 4, 295-305.

Creem-Regehr, S. H., Willemsen, P., Gooch, A. A., & Thompson, W. B. (2005). The influence of restricted viewing conditions on egocentric distance perception: Implications for real and virtual environments. Perception, 34, 191–204.

Cruz-Neira, C., Sandi, D. J., & DeFanti, T. A. (1993). Surround-screen projection-based virtual reality: the design and implementation of the CAVE. *Communications of the ACM*, June 1992, 64-72.

Dede, C., Salzman, M. C., Loftin, R. B., & Sprague, D., (1999). Multisensory immersion as a modeling environment for learning complex scientific concepts. In Roberts, Nancy & Fuerzig, W. (Eds.) *Computer Modeling and Simulation in Science Engineering* (pp. 282-319). New York, NY: Springer.

Dixon, J.K. (1997). Computer use and visualization in students' construction of reflection and rotation concepts. *School Science and Mathematics*, 97, 352–358.

Dori, Y. J. & Barak, M. (2001). Virtual and physical molecular modeling: fostering model perception and spatial understanding. *Educational Technology & Society*, 4, 1.

Drascic, D. (1991). Skill acquisition and task performance in teleoperation using monoscopic and sterescopic video remote viewing. *Proc. Human Factors Society's 35th Annual Meeting* (pp. 1367–1371). San Francisco: Human Factors Society.

Ekstrom, R. B., French, J. W., Harman, H. H., & Derman, D. (1976). Kit of Factor-Referenced Cognitive Tests. Princeton, NJ: Educational Testing Service. Executive functions in clinical settings: Problems and recommendations. *Seminars in Speech and Language*, 21, 169-183.

Galili I., Weizman A., & Cohon A. (2004). The sky as a topic in science education. *Science Education*, 88, 574–593.

Gonsalves, A. (2008). Intel, DreamWorks team on 3-D animation technology. Retrieved August 22, 2008 from: http://www.informationweek.com/news/personal_tech/TV_theater/showArticle.jhtml?articleID=210102160&subSection=Processors

Gotwals, R. R. (1995). Scientific visualization in chemistry, better living through chemistry, better chemistry through pictures: Scientific visualization for secondary chemistry students. In Thomas, D. A. (Ed.), *Scientific Visualization in Mathematics and Science Teaching* (pp. 153–179). Charlottesville: AACE.

Griffiths. A. K., & Preston, K. R. (1992). Grade-12 students' misconceptions relating to fundamental characteristics of atoms and molecules. *Journal of Research in Science Teaching*, 29, 611-628.

Hansen, J., Barnett, M., MaKinster, J., & Keating, T. (2004). The impact of three_dimensional computational modeling on student understanding of astronomical concepts: a quantitative analysis. *International Journal of Science Education*, 26, 1365- 1575.

Holford, D. G. & Kempa, R. F. (1970). The Effectiveness of Stereoscopic Viewing in the Learning of Spatial Relationships in Structural Chemistry. *Journal of Research in Science Teaching,* 7, 265-270.

Hsu, J., Pizlo, Z., Babbs, C. F., Chelberg, D. M., & Delp, E. J. (1994). Design of studies to test the effectiveness of stereo imaging truth or dare: is stereo viewing really better? *In Proceedings of SPIE*, 2177, 211-220.

Hu, H. H., Gooch, A. A., Creem-Regehr, S. H., & Thompson, W. B. (2002). Visual cues for perceiving distances from objects to surfaces. *Presence,* 11, 652-664.

Hubona, G. S., Wheeler, P. N., Shirah, G. W. & Brandt, M. (1999). The relative contributions of stereo, lighting, and background scenes in promoting 3D depth visualization. *ACM Transactions on Computer-Human Interaction*, 6, 214–242.

Kali, Y. (2006). Collaborative knowledge building using a design principles database. *International Journal of Computer Support for Collaborative Learning*, 1, 187-201.

Kalisperis, L. N., Otto, G., Muramoto, K., Gundrum, J. S., Masters, R., Orland, B. (2003). Virtual Reality/Space Visualization in Design Education: The VR-Desktop Initiative. *Proceedings of the 20th Conference on Education in Computer Aided Architectural Design in Europe.* Warsaw, Poland, 64-71.

Keating, T., Barnett, M., Barab, S. A., & Hay, K. E. (2002). The virtual solar system project: developing conceptual understanding of astronomical concepts through building 3D computational models. *Journal of Science Education & Technology*, 11, 261-275.

Khatau, C. (2008). Film goes back to the future with 3D. *CNN.com.* Retrieved Sept. 12, 2008 from http://www.cnn.com/2008/TECH/09/12/future.cinema/index.html

Kim, W. S., Ellis, S. R., Tyler, M. E., Hannaford, B., & Stark, L. W. (1987). Quantitative evaluation of perspective and stereoscopic displays in three-axis manual tracking tasks. *IEEE Transactions on Systems, Man, and Cybernetics,* 17, 61-72.

Klatzky, R. L. (1998). Allocentric and egocentric spatial representations: definitions, distinctions, and interconnections. In Freksa, C., Habel, C., & Wender, K. F. (Eds.), *Spatial Cognition: An Interdisciplinary Approach to Representing and Processing Spatial Knowledge.* (pp. 1 - 16). New York: Springer.

Kooi, F. L. & Toet, A. (2004). Visual comfort of binocular and 3D displays. *Displays,* 25, 99-

108.

Landey, M. S., Maloney, L. T., Johnston, E. B., and Young, M. (1996). Measurement and modeling of depth cue combination: in defense of weak fusion. *Vision Research,* 35, 389-412.

Mayer, R. E. (2005). Principles for reducing extraneous processing in multimedia learning: coherence, signaling, redundancy, spatial contiguity, and temporal contiguity principles. In R. E. Mayer (Ed.), *Cambridge handbook of multimedia learning* (pp. 183-200). New York, NY: Cambridge University Press.

Marr, D., & Nishihara, H. K. (1978). Representation and recognition of the spatial organization of 3D shapes. *Proceedings of the Royal Society of London*, *200, 269-294.*

Messner, J.I. and Horman, M.J., (2003) "Using Advanced Visualization Tools to Improve Construction Education," *Proceedings of CONVR 2003, Conference on Construction Applications of Virtual Reality*, Blacksburg, VA, pp. 145-155.

Morin, P. (2004). State of the geowall. Retrieved November 10, 2007, from http://geowall.geo.lsa.umich.edu/talks/StateoftheGeoWall.ppt

Nataupsky, M., & Crittenden, L. (1988). Stereo 3D and non-stereo presentations of a computer-generated pictorial primary flight display with pathway augmentation. In *Proceedings of the AIAA/IEEE 8th Digital Avionics System Conference* (pp. 552-557). New York: IEEE.

Norris, C., Sullivan, T. , Poirot, J. & Soloway, E. (2003) No access, no use, no impact: snapshot surveys of educational technology in k-12," *Journal of Research on Technology in Education*, 36, 15-28.

Ohno, N., Kageyama, A., & Kusano, K. 2006. Virtual reality visualization by CAVE with VFIVE and VTK. *Journal of Plasma Physics*, 72, 1069-1072

Okuyama, F. (1999). Evaluation of stereoscopic display with visual function and interview. *Proceedings of SPIE*, 3639, 28-35.

Paas, F., Tuovinen, J. E., Tabbers, H., & Van Gerven, P. W. M. (2003). Cognitive load measurement as a means to advance cognitive load theory. *Educational Psychologist*. 38(1), 63-71.

Paas, F. & Van Merriënboer, J. J. G. (1994). Instructional control of cognitive load in the training of complex cognitive tasks. *Educational Psychology Review*, 6, 351-371.

Parker, J. & Heywood, D. (1998). The earth and beyond: developing primary teachers' understanding of basic astronomical events. *International Journal of Science Education*, 20, 503-520.

Parrish, R. V., Busquets, A. M., Williams, S.P. (1990). Recent research results in stereo 3-D pictorial displays at the Langley Research Center. In *Proceedings IEEE/AIAA/NASA 9th Digital Avionics Systems Conference, IEEE Catalog No. 90CH2929-8.* (pp. 529-539), Virginia Beach: , Inst. of Electrical and Electronics Engineers, Inc.,

Pepper, R L, Smith, D.C., Cole, R. E. (1981). Stereo TV improves operator performance under degraded visibility conditions. *Optical Engineering*, 20, 579-585.

Pixar (2008). The Walt Disney Studios rolls out slate of 10 new animated motion pictures through 2012. Retrieved September 12, 2008 from http://www.pixar.com/companyinfo/press_box/news/20080408.htm

Reinhart, W. F., Beaton, R. J., & Snyder, H. L. (1990). Depth cueing for visual search and cursor positioning. *Proc. SPIE Stereoscopic Displays and Applications*, 1256, 12–21.

Roberts, D. (2000). Media and youth: Access, exposure, and privatization. *Journal of Adolescent Health.* 278, 8-14.

Seddon, G. M., & Eniaiyeju, P. A. (1986). The understanding of pictorial depth cues, and the ability to visualise the rotation of 3D structures in diagrams. *Research in Science and Technological Education*, 4, 29 – 37.

Shah, P., & Miyake, A. (1996). The separability of working memory resources for spatial thinking and language processing: An individual differences approach. *Journal of Experimental Psychology: General*, 125, 4-27.

Sherman, S. (1996). A set of one's own: TV sets in children's bedrooms. *Journal of Advertising Research.* 36, 9-12.

Shubbar, K. E. (1990). Learning the visualization of rotations in diagrams of 3D structures. *Research in Science and Technological Education*, 8, 145 – 154.

St. John, M., Cowen, M. B., Smallman, H. S. & Oonk, H. M. (2001). The use of 2D and 3D displays for shape-understanding versus relative-position tasks. *Human Factors*, 43, 79-98.

Steinwand, D. R., Davis, B., Weeks, N. (2003). Geowall: investigations into low-cost stereo display technologies. (Open-File Report 03-198). Sioux Falls, SD: U.S. Department of the Interior.

Surdick, R. T., Davis, E. T., King, R. A., & Hodges, L. F. (1997). The perception of distance in simulated visual displays – a comparison of the effectiveness and accuracy of multiple depth cues across viewing distances. *Presence: Teleoperators and Virtual Environments,* 6, 513-531.

Sweller, J. (1988). "Cognitive load during problem solving: Effects on learning". *Cognitive Science,* 12, 257-285

Tarr M. J. & Pinker, S. (1990). When does human object recognition use a viewer-centered reference frame? *Psychological Science*, 1, 253-256.

Tieman, A. (2008). CES: Dual-view and 3D high-definition TV. Retrieved August 20, 2008 from http://ces.cnet.com/8301-1_1-9844458-67.html

Tory, M., Kirkpatrick, A. E., Atkins, M. S., Möller, T. (2006). Visualization task performance with 2D, 3D and combination displays. *IEEE Transactions on Visualization and Computer graphics,* 12, 2-13.

Trindade, J., Fiolhais, C., & Almeida, L. (2002). Science learning in virtual environments: a descriptive study. *British Journal of Educational Technology*, 33, 471-488.

Tuckey, H., Selvaratnam, M., & Bradley, J. (1991). Identification and Rectification of Student Difficulties Concerning 3D Structures, Rotation, and Reflection. *Journal of Chemical Education,* 68, 460-464

Tversky, B. (2005). Functional significance of visuospatial thinking. In P. Shah & A. Miyake (Eds.), *Cambridge Handbook of Visuospatial Thinking (*pp. 1–34). New York: Cambridge.

Wang, H-C., Chang, C-Y., & Li, T-Y. (2007). The comparative efficacy of 2D- versus 3D-based media design for influencing spatial visualization skills. *Computers in Human Behavior,* 23, 1943-1957.

Wanger, L. R., Ferwerda, J. A., & Greenberg, D. P. (1992). Perceiving spatial relationships in computer-generated images. *IEEE Computer Graphics & Applications,* 12, 44-58.

Ware, C. and Franck, G. (1996). Evaluating stereo and motion cues for visualizing information nets in three dimensions. *ACM Transactions on Graphics*, 15, 121-140.

Warren, C. (2008) Stereoscopic 3D gaming history made at SIGGRAPH 2008. Press release.

Retrieved August 22, 2008 from http://www.marketwatch.com/news/story/stereoscopic-3d-gaming-history-made/story.aspx?guid={8F516E2E-3782-47BD-BAC4-DBEFCFE0BE2F}&dist=hppr

Wheatstone, C. (1852). Contributions to the physiology of vision: Part the second. On some remarkable, and hitherto unobserved, phenomena of binocular vision. *Philosophical Transactions of the Royal Society, 142,* 1-17.

Wickens, C. D., Merwin, D. H., Lin, E. L. (1994) Implications of graphics enhancements for the visualization of scientific data: dimensional integrality, stereopsis, motion and mesh. *Human Factors*, 36, 44-61.

Wickens, C. D., Vincow, M., & Yeh, M. (2005). Design Applications of Visual Spatial Thinking. In P. Shah & A. Miyake (Ed.), *Cambridge handbook of visuospatial thinking* (pp. 383-425). New York, NY: Cambridge University Press.

Willemsen, P., Gooch, A. A., Thompson, W. B., Creem-Regehr, S. H. (2008). Effects of stereo viewing conditions on distance perception in virtual environments. *Presence,* 17, 91-101.

Williams, D. (2006). A brief social history of game play. In P. Vorderer & J. Bryant (Eds.), *Playing video games: Motives, responses, and consequences* (pp. 197-212). Mahwah, NJ: Erlbaum.

Wu, G., & Cheng, I. (2007). An interactive 3D environment for computer based education. IEEE Int'l Conference on Multimedia (pp. 1834-1837), July, 2007, Beijing, China.

Wu, H.-K., Krajcik, J. S., & Soloway, E. (2001). Promoting understanding of chemical representations: Students' use of a visualization tool in the classroom. *Journal of Research in Science Teaching*, 38, 821 – 842.

Wu, H-K. & Shaw, P. (2004). Exploring visuospatial thinking in chemistry learning. *Science Education*, 88, 465-492.

Yeh, Y.Y and Silverstein, L. D. Spatial judgments with monoscopic and stereoscopic presentation of perspective displays. *Human Factors*, 34, 583-600.

Zacks, J., Levy, E., Tversky, B., & Schiano, D. J. (1998). Reading bar graphs: effects of extraneous depth cues and graphical context. *Journal of Experimental Psychology: Applied,* 4, 119-138.

Table 1

Means for Task Performance

Task	*N*		*M*		*SD*	
	2D	Stereo	2D	Stereo	2D	Stereo
Letter rotation	19	18	.54	.50	.04	.05
Block rotation	19	18	.50	.47	.08	.08
Paper folding	19	19	.61	.49	.06	.06
Subtotals			.55	.49	.11	.11

Note. Means consist of normalized scores. SD subtotal is the SD of all three tasks of that presentation type added in quadrature.

Table 2

Analysis of Variance for Performance

Source	*df*	*F*	h	*p*
		Fixed effects		
Presentation (P)	1	1.03	.053	.32
Task (T)	2	.39	.021	.68
P x T	2	.53	.030	.59
		Random effects		
Student (S)	18	1.36	.53	.25
P x S	18	1.22	.39	.30
T x S	36	1.97	.68	.03*

Table 3

Means for Time on Task

Task	*N*		*M* (seconds)		*SD*	
	2D	Stereo	2D	Stereo	2D	Stereo
Letter rotation	18	19	18.0	12.6	1.6	0.8
Block rotation	19	16	18.6	24.5	7.4	8.5
Paper folding	18	18	21.2	34.9	1.9	3.6
Subtotal			19.3	24.0	7.8	9.3

Note. SD subtotal is the SD of all three tasks of that presentation type added in quadrature.

Table 4

Analysis of Variance for Time on Task

Source	*df*	*F*	h	*p*
		Fixed effects		
Presentation (P)	1	11.6	.40	.00**
Task (T)	2	16.4	.49	.00**
P x T	2	23.8	.60	.00**
		Random effects		
Student (S)	18	1.57	.52	.14
P x S	18	1.40	.43	.20
T x S	36	2.54	.73	.01*

Table 5

Means for Representational Environment Preference

Task	*N*	*M*	*SD*
Letter rotation	19	1.42	.77
Block rotation	18	1.17	.88
Paper folding	18	.94	1.12

Note. Means are on a scale of 0 = 2D preference and 2 = stereoscopic preference.

Figure Captions

Figure 1. Sample of a 2D (left) and 3D (right) representation of a simple house.

Figure 2. A sample of the letter rotation task.

Figure 3. A sample of the paper folding task. In the stereoscopic version, the top and bottom parts of the folded paper appear to come out from the screen towards the viewer.

Figure 4. A sample of the block rotation task, using a Mars rover as the analog. In the stereoscopic version, the rover appears to come out from the screen towards the viewer.

Figure 5. The Space Visualization Laboratory at the Adler Planetarium and Astronomy Museum.

Figure 1

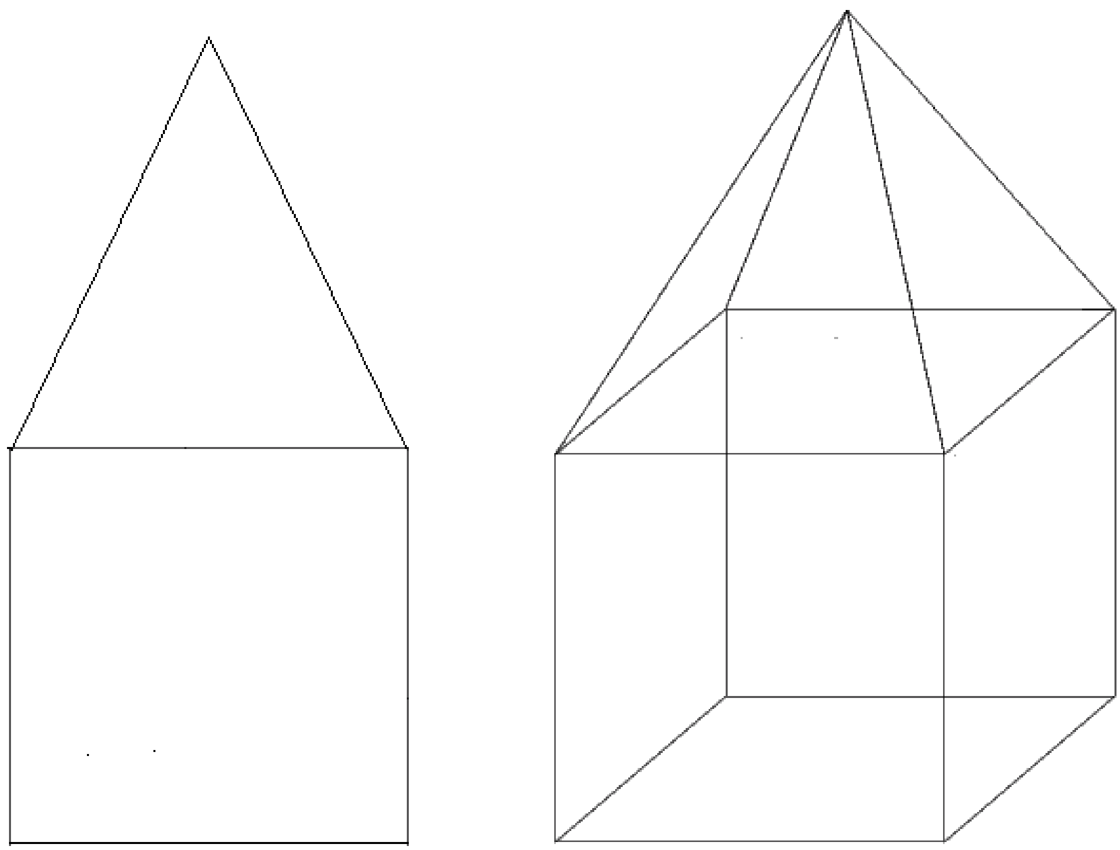

Figure 2

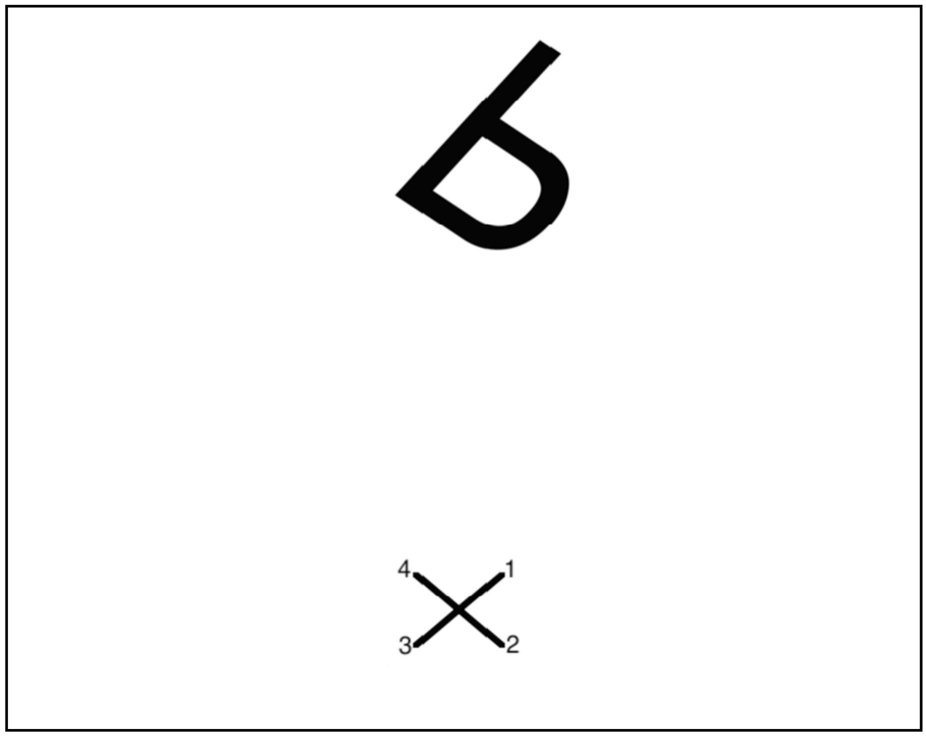

Figure 3

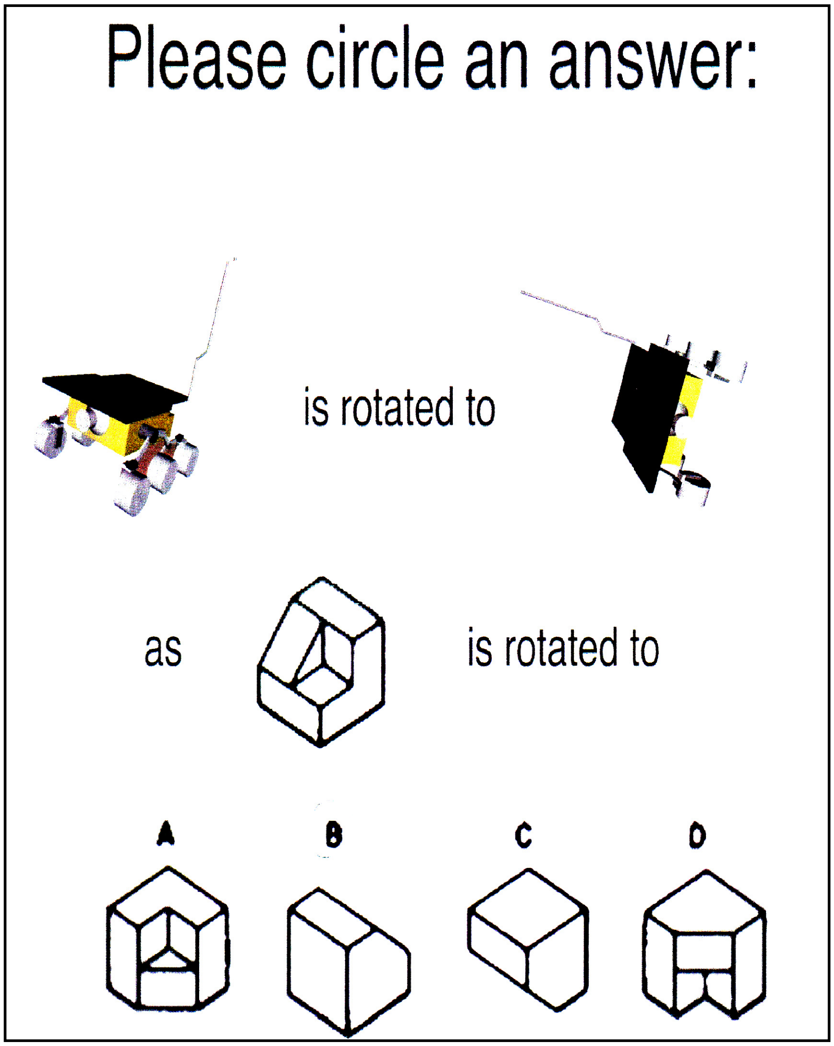

Figure 4

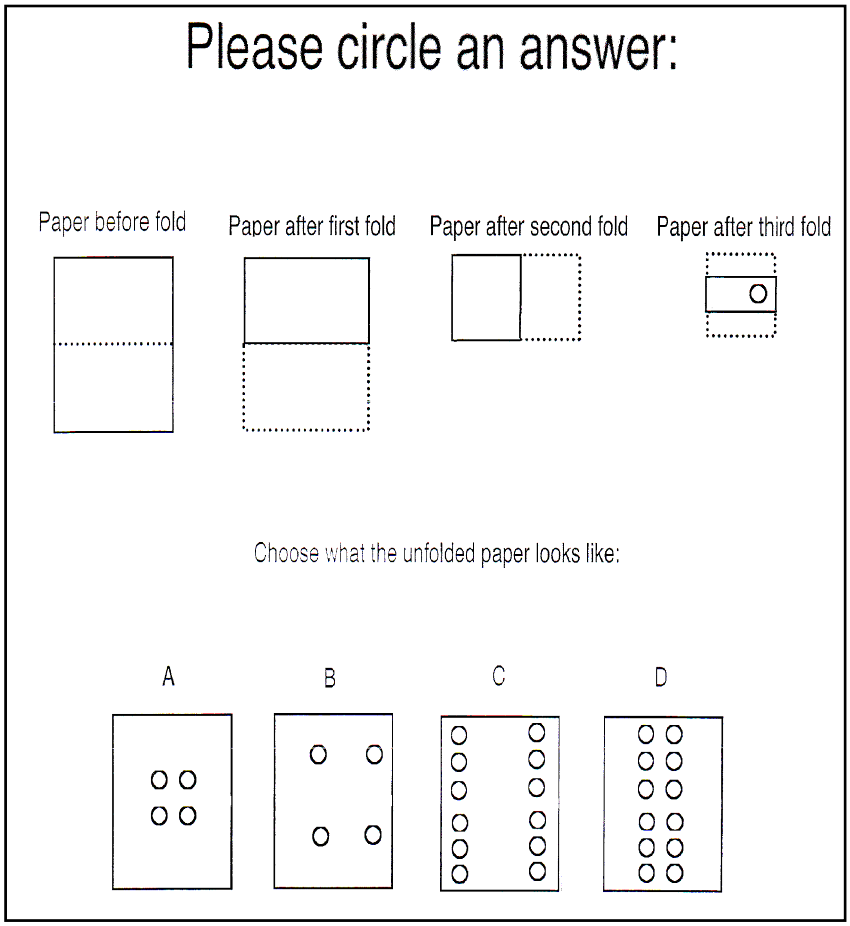
Please circle an answer:
Paper before fold
Paper after first fold
Paper after second fold
Paper after third fold
Choose what the unfolded paper looks like:
A
B
C
D

Figure 5