UNDERSTANDING WHAT MAKES 3D VISUALIZATIONS DIFFICULT

By

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ABSTRACT OF THE THESIS

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Three dimensional visualizations are used in numerous fields to help people gain a better understanding of the subject. Because these visualizations are growing both in prevalence and in complexity, it is becoming increasingly important that people understand them. Prior studies demonstrate that this is not the case with a significant portion of the population. This suggests that we either make the visualizations easier or provide adequate training through our education venues to help people understand 3D visualizations. Unfortunately, making visualizations easier is not always an option because the visualization is necessarily hard because of the problem being tackled, e.g., viewing an MRI scan of a human being. Currently, little is done in our education systems for improving 3D visualization comprehension. This may be because we are not really sure how to teach such skills. To be able to train people in comprehending 3D visualizations, we need to understand how people comprehend and process these visualizations which is a non-trivial task.

Overall, the goal of this thesis is to determine what properties of 3D visualizations make their comprehension difficult. In order to do so, a visualization test was designed to assess the ability of subjects to understand the internal structure of 3D block diagrams.
This test was administered to subjects who were videotaped solving the visualization problems. An analysis of the verbal protocols of these subjects identified strategies that subjects used to process the 3D visualizations and problem areas where they provided inaccurate solutions. The analysis uncovered those visualization properties that created difficulties for subjects and also suggested training methods for presenting these properties in a way that would help improve the ability of individuals to comprehend visualizations.
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Chapter 1

1. Introduction

Scientific Visualizations are used in various fields to convey important information that is often difficult to explain verbally, e.g., diagrams in science textbooks. Visualizations are often used to discover important relationships that a scientist may not have even known existed. In medicine, such visualizations may provide important diagnostic cues. Overall, a wide variety of activities such as airport security, medical diagnosis, internet search representation, education and geological research readily take advantage of scientific visualizations. For example, a bathymetric presentation of sea floor height provides a good overview of plate tectonics to geologists. These visualizations are meant to enhance understanding and comprehension of the underlying data by visually presenting the relationships between different aspects of the data. Research has shown that scientific visualizations also can aid learning in scientific fields such as physics, geology, chemistry and biology. They are often used to this end to present concepts, e.g., the schematic drawings of the earth’s layers in geology to represent sedimentation over millennia. The use of visualizations has also been seen to improve productivity in performing many ordinary tasks. For example, 2D visualizations were seen to help shorten search times when users were given the task of locating emails in a list of emails [1].

Although visualizations are believed to provide an easier understanding of a subject matter, a significant portion of the population have difficulty with the visualization representations, that is, the figures and drawings used to illustrate the underlying subject matter. This is particularly true with three dimensional visualizations.
These figures are typically two-dimensional representations of a 3D world but some people do not see this relationship with a 3D world. This is not surprising! The world of art was transformed in the 14th century when Lorenzo Ghiberti began to paint in perspective with figures and objects that were to be in the distance reduced in size governed by a cone projected on the eye [2]. He based his work on a 12th century Iraqi mathematician and physicist’s book on optics [3] which had been recently translated into Italian. This approach was central to the development of the pyramid perspective that is used in artwork up to this day.

An inability to see the 3D relationships in the 2D representations will thus make it difficult for a person to make inferences about the scientific relationships the visualization is trying to illustrate. In a study of geology students that had recently started their studies, at least fifty percent had trouble understanding the earth cross-section visualizations that were supposed to make their learning easier [4]. Since many users of scientific visualizations struggle with comprehending them, such visualizations may actually be detrimental in helping users understand the concepts presented. Unlike many other skills such as literacy and numeracy, students in primary and secondary education rarely go through significant visualization training beyond understanding simple 2D graphs. Thus, we have a conundrum developing in this world of modern science. Visualizations are being increasingly used and have been shown to be quite effective, but many people are unable to take advantage of them because there is little in the way of formal training programs that give people the appropriate skills in visualization literacy that they need to understand the visualizations.
The ability to understand 3D visualizations has been demonstrated to be related to an individual’s spatial ability ([5][6]). Previous research has also shown that spatial abilities vary greatly among different individuals and that there are many different types of spatial ability [7]. In addition, research has shown that there is a measurable gender difference in spatial abilities. For example, males were found to achieve significantly higher accuracy than females on a test that measured comprehension of orthogonal projection visualizations [6].

The inability to comprehend 3D visualizations may dissuade many otherwise qualified individuals from pursuing careers which require visualization comprehension. Prior research has found that a significant portion of university students have difficulty with understanding the very visual images that are meant to enhance the comprehension of the subjects being studied [8]. This, alone, may cause students to perform poorly in the subject matter and select another career path than one they may have otherwise pursued.

Visualization comprehension difficulties can also cause errors in interpretation that may result in costly mistakes. For example, x-rays visualizations are typically used to examine baggage that travelers will be bringing with them on a plane. If there are misinterpretations in reading the visualizations, the safety of many individuals may be compromised ([9],[10]). Computing technology now allows a greater number of visualizations to be generated at little effort, therefore increasing their use. As more and more visualizations are used in a broadening set of applications, e.g., a display of electricity usage in the home, economic reports in newspapers and a display of voting patterns of elected officials, the need to improve visualization comprehension increases.
Often times, users of technology are inherently expected to understand figures and images in information handling tasks they are assigned without anyone determining whether the very images presented can be understood by the individuals using the technology.

Thus, the prevalence and ubiquity of these visualizations make it crucial to create means to help people build up the basic analytical skills necessary to understand them. Research has indicated that comprehension of visualizations can be improved by training users to understand visualizations through practice. For example, the time spent doing course assignments in earth science classes was seen to correlate to the ability of subjects to understand the 3D space diagrams used in the course [11]. This suggests that building up spatial abilities in the general population through education may allow a greater overall comprehension of 3D visualizations.

1.1 Motivation

Although there is a good deal of research that has been done on the difficulty people have with 3D visualizations and how visualization comprehension skill relates to spatial ability, little research has been done on understanding what makes visualizations so difficult to comprehend. The exploratory study in this thesis will therefore look at what strategies people use to comprehend visualizations and also what visual properties make 3D visualizations difficult to understand. Given that this is a thesis in electrical and computer engineering, it will not attempt the hubris of trying to build a psychological model of how humans think and resolve visualization problems, but rather it will take the more practical approach of determining what strategies individuals are observed to use in
solving a comprehension problem. The purpose of capturing these strategies will be to use them in future research that will build visualization comprehension training modules. The study will also look at those visualization problems which were found to be incredibly difficult or intractable to comprehend by problem solvers. From a comparison of these problems to problems which were solvable, it is hoped to determine exactly what visual properties (orientation, shape of object, intersection of internal objects, etc.) might be responsible for the difficulties a person had with the problem. Uncovering such information will make it possible to recommend designs to avoid in building scientific visualizations and also what types of comprehension skills might need to be taught to make such visualizations understandable, e.g., a possible animation of the formation of the visualization so that the interaction of its various components is understood. Overall, the intent of the work in this thesis is to gain a better understanding of what makes 3D visualizations difficult for the user and to use that knowledge to develop visualization training methods that will teach visualization comprehension skills. In addition this information can be used to enable the creation of visualizations that minimize properties that may hinder comprehension while still conveying the necessary information for the user. Although the work that is being done in this thesis deals with only one kind of 3D visualization, many of the findings are expected to be relevant to general visualization comprehension skills.

1.2 Type of 3D Visualization Problem Used in Exploratory Study

There are many different forms that scientific visualizations take and many different 3D visualizations. Because each such visualization adds its own complexity to
user comprehension, it was reasoned that only one visualization type would be used in
the exploratory study. However, which type to choose from the many available became
the next problem to resolve in this work. Several attempts have been made to categorize
scientific visualization [13]. These categorizations are based on the types of software
processing that were used to create the visualizations and thus, not related to how such
visualizations are comprehended so not useful in guiding the selection of a visualization
type. It was decided to use a common type that was prevalent in geology and
oceanography, e.g., a 3D visualization that is commonly termed a “space-filling” or
“block” visualization. This is illustrated in Figure 1 which shows the existence of fault
lines in the sedimentary layers of the earth. In essence, the structure fills a space defined
by the 3D outlines of the figure. How it fills that space is evident by what can be seen on
each side of the structure, e.g., the sedimentary layers. Geology uses space-filling
visualizations to illustrate how changes to the earth that occurred a long time ago can be
interpreted from the patterns found in the visualization. A student needs to visualize the
visualization's outside layers as not just a surface pattern but representing a continuing set
of layers that go completely through the 3D structure shown with the final interpretation
being one of sediment layers and disruptive changes taking place to a larger section of the
earth such as a volcanic valley. Since comprehending a space-filling visualization
requires a person to imagine what is happening internally in the structure based on
external cues, the comprehension problem chosen for the study was one of asking
subjects what a “slice” taken somewhere through the space-filling visualization would
look like. Figure 2a illustrates this problem with the slice shown. Figure 2b provides the
answer to the problem.
1.3 Research Plan

For this research subjects were given a wide variety of space-filling slice problems and asked to draw what would appear on the slice. This required subjects to imagine the continuation of patterns or shapes that they saw on the external portions of the structure they were viewing. To obtain the reasons for their solutions, subjects were asked to both draw what they thought the answer was and to talk aloud while they created their solution. The verbalized strategies used, the mistakes made, the corrections and the comparisons of success and failure on the different problems were then used to build hypotheses about what properties of the slice or the visualization caused mistakes and
comprehension difficulties and what strategies (both poor and good) subjects used to solve the problems.

Before beginning such a videotaped study, however, it was necessary to both create a representative set of problems to use and also to determine approximately which problems were harder than others so that the set of problems could be sorted for our subjects from easy to hard to avoid giving the most difficult problems to the subject first. The set of problems were gathered from introductory geology textbooks. These were expanded by an artist that was hired to assist the project. These problems were then solved by all project research personnel who then rank ordered the difficulty of the problems. A total of 35 problems were created. These are shown in Appendix A1 Index of Preliminary Experiment Diagrams.

1.4 Outline of Thesis

The structure of this thesis is as follows: Chapter 2 discusses related research involving studies of 3D visualizations and explains why the work in this thesis is unique and novel. It also explains relevant work done on the psychology of spatial comprehension in order to support the more pragmatic approach of this thesis – that is, to focus on what might be viable training strategies for comprehending visualizations. Chapter 3 describes the rank ordering process used to initially determine visualization difficulty and provides underlying reasons for the space-filling problems chosen. Chapter 4 presents an overview of the verbal protocol study that constitutes the basis of this research. It first discusses the pilot studies through which the final problem sets evolved and then presents the methodology used to run the verbal protocol study.
Chapter 5 presents the methods used for analyzing the verbalizations and sketches of the subjects. It also addresses the reliability of the coding that was carried out. Following this, a brief analysis of the results from the study is presented. The strategies used by the subjects and the visualization properties that were found to be difficult for the subjects to comprehend are discussed along with an assessment of how valid the results are believed to be given the low number of subjects. Chapter 6 discusses the conclusions drawn from the results and how the field of visualization literacy can use the findings both to create effective education and also more comprehensible visualizations. Finally Chapter 7 lists the overall contributions of the thesis and summarizes what was done and discovered.
Chapter 2

2. Literature Review

2.1 Introduction

The growing use of 3D visualization in current society has increased the need for visualization literacy, that is, the set of skills and strategies required to appropriately interpret visualizations [14]. However, a number of studies show that people have problems in comprehending 3D visualizations both in academia and in industry, which leads to difficulties in understanding some key subject areas. This can lead to several negative consequences. For instance, Kali and Orion [4] found that geology students with weak spatial abilities could not understand basic geologic structures. They determined that many of the students in their study had significant difficulties with the key concepts that are taught in introductory undergraduate college geology because they could not understand the geology diagrams used in the course.

Fortunately, previous studies show that visualization literacy can be improved with better visualizations or proper training ([13], [15], [16], [17], [18], [19]). Unfortunately, most people are not exposed to visualization education in their primary and secondary education programs and do not have opportunities to get proper training to improve their visualization literacy. Thus, there is an urgent need for developing a training program that can enhance people’s visualization comprehension skills. To develop an effective training program, it is critical to understand what strategies people actually use in interpreting visualizations and what visual properties make visualizations difficult to comprehend. However, in spite of obvious evidence of people having trouble
in interpreting visualizations properly, little research has been done on investigating what makes 3D visualizations so difficult to comprehend [13]. Thus, there is a need for research which investigates what makes visualizations so difficult.

This chapter reviews studies of 3D visualizations including the pervasiveness of 3D visualizations, problems people are having in comprehending visualizations, impacts of these problems and spatial comprehension studies related to visualizations in order to highlight the necessity and importance of this thesis that investigates what visual properties makes visualizations difficult to comprehend.

2.2 Pervasiveness of 3D visualizations

As the graphical capabilities of computers grow, the realistic 3D visualizations generated by computers have become exceedingly prevalent. An increasing number of fields are using visualizations such that 3D visualizations are common in everyday life [6]. With the prevalence of 3D visualizations, proper comprehension of these 3D visualizations is necessary for success in many different fields including geology, biology, astronomy, architecture, medical science and many engineering disciplines. Moreover, textbooks used in primary and secondary education also use a number of computer generated visualizations to illustrate concepts such as geologic processes in earth sciences and crystal structures in chemistry making the ability to comprehend 2D representations of 3D objects one of the critical elements in learning. This pervasiveness of visualizations in all realms in our lives makes it increasingly important to gain visualization comprehension skills.
2.3 Problems of comprehension

Regardless of the prevalence of visualizations and the importance of having visualization comprehension skills, research shows that a significant percentage of the general population cannot adequately comprehend even basic 3D visualization concepts. For instance, Kali and Onion [4] found that many introductory geology students did not have the ability to understand basic geology structures. In addition, despite its importance, visualization literacy is not taught in primary or secondary education which may be the result of inadequate education materials, school policies or simply not knowing that these skills are both missing and essential.

It is also important to note that there are individual differences in perceiving images and understanding visualizations. For example, Blajenkova, Kozhevnikov and Motes [21] assessed individual differences in visual imagery preferences and experiences, and reported that differences in visualization comprehension among individuals varied greatly. Similarly, Alle [20] who examined the 3D spatial abilities of geology students reported that students’ visual penetrative ability varied, greatly. Blajenkova, Kozhevnikov and Motes [21] found individual differences by professions, with scientists showing higher preferences and experiences for spatial imagery than artists or humanity professionals. Many researchers ([22], [16], [23], [24], [25], [18], [26], [6]) also reported gender differences in spatial abilities with males showing higher spatial abilities than females. Thus, it appears that visualization literacy is highly related to career choices and may have a role in gender discrimination in the sciences suggesting that effective training methods are likely to also have an important social benefit.
Although both the number of visualizations and the importance of visualization literacy are increasing, people do not have the proper skills and strategies to comprehend visualizations effectively. It is not only the pervasiveness, but also the increasing complexity of visualizations brought on by the ease of generating such visualizations with canned computer graphics programs that are making them an even more serious problem than before. People can no longer be simply categorized into two categories, those with visualization comprehension skills and those without. Some visualizations are too hard for anyone to see all the nuances and meanings embedded in them unless such people are skilled technicians familiar with the particular visualization. The use of visualizations is becoming such that it is now essential to train people in specific task visualizations, i.e., the scanning of suitcases for illegal objects [9] or the rotation of pictures of human bone structure [27]. Although a variety of training programs have been developed, no one has looked at how to best create such programs nor what features of the visualizations to emphasize in the training.

2.4 Impact of problems of comprehension

There are numerous problems that can be caused by the inability to comprehend visualizations properly. The lack of visualization comprehension skills can discourage the pursuit of scientific careers, hinder learning, and makes it difficult to function effectively in daily life. For example, there are an increasing number of professions that require a high level of visualization literacy. In addition, in those professions, lack of skills and strategies in comprehending visualizations can cause costly mistakes. For instance, in the security industry, if people responsible for monitoring suspicious objects misinterpret 3D
visualizations of those objects, the consequences could lead to the loss of life. Medical technology has also been taking great advantage of the use of visualizations in the recent years. Lack of skill in understanding 3D medical images can lead to misdiagnoses of illness and surgical errors. Thus, people who have weak visualization comprehension skills may feel discouraged to pursue careers in such areas.

As a second example, visualization literacy is so closely related to learning that lack of visualization comprehension skills may hinder proper learning of any subject matter using visualizations to convey information. A growing numbers of disciplines now require visualization literacy to properly learn fundamental concepts in the discipline. These include architecture, geology, medicine, dentistry, biology, chemistry, engineering and physics. A psychologist and geologist [28, p 144] recently stated that “For efficient and geologically adaptable thinking, one prerequisite is probably of universal value, whatever the nature of the geological content. This is the skill for thinking in three dimensions, for visualizing shapes in the mind’s eye, rotating, translating and shearing them” which illustrates the important role of visualization literacy in choosing any aspect of Geology as a career. Black [11] examined the relationship between understanding of earth science concepts and spatial abilities. He used the Earth Science Concept (ESC) test which is designed to test earth science misconceptions. His spatial ability measures included mental rotation, spatial perception and spatial visualization. He found a positive correlation between earth science conceptual understanding and the spatial abilities. While all three of the spatial ability test scores showed some correlation with the ESC test scores, the mental rotation spatial ability test scores correlated most highly with the ESC test scores indicating a strong relationship between spatial abilities and practical
science comprehension skills. In a similar vein, Hegarty, Keehner, Khooshabeh and Montello [17] also found that spatial ability was predictive of performance in restorative dental practical laboratory classes. Thus, a lack of key spatial abilities may hinder effective learning and discourage the pursuit of study in even dentistry. But visualization training has been shown to overcome these spatial ability deficits [13]. To be more specific, many individuals may be otherwise qualified to study in professions using visualizations, but due to lack of visualization training, they will not be able to understand basic course material and thus, be discouraged from entering promising careers.

Furthermore, since visualizations are so prevalent in everyday life, problems in comprehending visualizations make it difficult to work and perform effectively in the everyday world. As a simple example, if an individual cannot read maps properly, he/she may constantly get lost in a new area. Such a situation becomes even more problematic if a close by trucker jams their GPS signal. A similar lack of visualization comprehension skills may cause inadequate interpretations of weather predictions, stock market performance and even horse racing data.

Thus, there is a need for solving this problem of visualization illiteracy. There can be two possible solutions. The first solution is to improve visualizations in a way that makes them easier to understand. The second solution is to develop and provide effective visualization comprehension training methods to help people learn skills and strategies to better comprehend a variety of typical visualization types. For both solutions, it is critical to understand what visual properties make 3D visualizations difficult to interpret and what strategies people use to understand visualizations. This knowledge will aid
designers in minimizing those characteristics of visualizations that are difficult to comprehend when they create visualizations, and provide practical data to researchers on how to develop effective visualization comprehension training methods.

2.5 Previous research in visualization literacy

Researchers have looked at individual differences in comprehending visualizations, in particular, how visualization comprehension skills relate to spatial ability. However, there is little previous research that specifically investigates what visual properties make visualizations difficult to interpret [6]. Hegarty, Keeher, Khooshabeh and Montello [17] studied the influence of dental education on spatial abilities. In this study, dental students were assessed on several measures including spatial ability, reasoning ability and the ability to infer the appearance of a cross-section of a 3D object, i.e., a tooth or partial tooth. The cross-section test is similar to the visualization test used in this thesis which asks subjects to infer the internal structure of 3D block diagrams. In Hegarty et al.’s study, the cross-section tests exhibited a positive correlation with spatial ability measures suggesting that students who entered the program had higher than average spatial abilities. In addition, the researchers found that although dental education did not improve the spatial abilities of the students in later years in their dental education, those students were significantly better in mentally manipulating representations of 3D structures of teeth than students in their early years. Thus, this study showed that although inherent spatial ability may not have improved, visualization literacy did improve. This suggests that visualization literacy training at an earlier time in a person’s
education may also be effective and possibly make more career choices available to young people.

Alle [20] conducted a study to measure and characterize the 3D spatial abilities of introductory geology lab students by testing their ability to understand the 3D structure of folded sedimentary rocks from visualizations of their surface structures. This ability, which is labeled Visual Penetrative Ability (VPA) in the geology field, is a basic skill that geology students need to have to understand the concepts taught in the field. In Alle's study, he provided four sessions of lab-based learning exercises, one included two different sessions using a computer-based training program, called Geo3D, and another included two different sessions using standard paper-and-pencil lab-based learning exercises. Pre-tests and post-tests measuring spatial ability were given before and after the training exercises. Alle found that for all four sessions, the performance was the same, indicating that there was no advantage to using Geo3D. What is important to note in this study is individuals’ varying VPA in solving spatial problems that was revealed by post interviews. Students with high VPA rapidly constructed a complete 3D model and after some mental processing, were able to draw cross-sectionals and face completion diagrams of the slices for geological structures that were based on their surface information only. Students with low VPA did not associate the surface information of the geological structures with the internal information of the structures and their attempts to draw the cross-sections showed many common non-penetrative errors. This study therefore, highlights the importance of providing training that illustrates the relationship between the external visible visualization properties and what they represent internally in the visualization.
Blajenkova, Kozhevnikov and Motes [21] also assessed individual differences in preferences and experiences for visual imagery by developing and validating the Object-Spatial Imagery Questionnaire (OSIQ). OSIQ is a self-report instrument assessing how an individual views and interprets external scenes. The basic assumption of OSIQ is that humans use two distinct visual comprehension subsystems, i.e., an object imagery system and a spatial imagery system. Each subsystem encodes and processes visual information in different ways. An object imagery system encodes and processes the accurate representations of the appearances of objects such as form, size, shape and color. A spatial imagery system encodes and processes abstract representations of the spatial relations among objects such as location of objects in space and spatial transformations. The questionnaire is made up of two scales; an object scale that assesses preferences for representing and processing high-resolution images of individual objects, and a spatial imagery scale that assesses preferences for representing and processing schematic images, spatial relations between objects, and spatial transformations. By using this questionnaire, the researchers found that preference for the object imagery scale was significantly correlated with high performance on object imagery tasks such as remembering how many windows were in a house picture, while preference for the spatial imagery scale was significantly correlated with high performance on spatial imagery tasks such as noting that the forest was behind the house. Strong Individual differences in preferences by professions were found. In the case of object imagery, visual artists showed higher scores than scientists and humanities professionals while scientists showed higher scores than visual artists and humanities professionals on the spatial imagery scale. This result is also found in Kozhevnikov, Kosslyn and Shephard’s
[5] study and indicates that there are differences by professions in understanding the same visual images. Although, this may result from a person’s genetically determined abilities, there are also possibilities that this results from the frequent exposure to tasks requiring one type of imagery interpretation. For instance, visual artists may have higher object imagery scores as they mostly use object imagery in their training and work, while scientists show higher spatial imagery scores because they often use spatial imagery in their training and work. This study reveals that there are individual differences by professions in the interpretation of visual images but not the source of these differences. These differences most certainly translate to differences in viewing visualizations suggesting that researchers work on understanding what causes these differences and how they are learned in order to be able to teach these skills more effectively.

Kali and Orion [4] examined how high school students solve structural geology problems. In their study, the authors identified two different types of answers to the problems they posed, non penetrative answers that were based on the external view of the structure, and penetrative answers that represented the internal properties of the structure. The authors found that those students who used penetrative strategies had higher spatial ability scores. In addition, as shown in other studies, the researchers found and reported large individual differences in VPA. In particular, males had significantly higher VPAs than females. The authors also reported that both VPA and the ability to perceive the spatial configuration of the structure were important skills used to solve the problems on the geologic spatial ability test. Thus, this study identified two different types of strategies used by subjects, i.e., the penetrative and non penetrative strategies with the penetrative strategy being more effective. The implication here is that training
individuals to comprehend visualizations needs to focus on methods that emphasize the penetrative strategy. Overall, the results suggests that by better understanding the strategies used to solve visualization problems, training programs can be built that promote the use of the more effective strategies.

As previously mentioned, there are only a few studies that identified those properties of visualizations that make them difficult to comprehend. Velez’ study [13] tried to identify elements in the visualizations that influenced people’s ability to create a mental picture of an object in projection visualizations. She also examined what spatial abilities affected visualization comprehension. To test visualization comprehension abilities, she asked subjects to form a mental picture of a 3D object based on its 2D orthogonal projections and then pick the correct 3D object from a set of four possibilities after the projection visualization was removed. Accuracy on selecting the correct 3D image was compared to six different spatial ability tests. Using the six spatial factors defined by Kimura [25], i.e., spatial orientation, spatial location memory, targeting, spatial visualization, disembedding and spatial perception, Velez found that accuracy on the visualization comprehension test had a medium-high correlation with spatial orientation and spatial visualization scores. She then used these scores to sort the visualization comprehension problems into high, medium and low difficulty. She reasoned that problems which high spatial ability subjects failed on were extremely difficult and that problems which low spatial ability subjects succeeded on were extremely easy. Properties of the visualizations were then listed, e.g., number of invisible edges, number of invisible vertices, overall number of vertices, off-axis angle of object position, etc. These were correlated with subject accuracy using spatial ability as
a control. It was found that off-axis angles followed by invisible vertices and edges were the properties that caused the most difficulty for the subjects. A training program was then developed which presented the same projection visualization problems but ordered them from easy to hard (based on the evaluation of properties) and provided mass practice involving each individual property to subjects. A second training program randomized these same problems. Subjects with similar spatial abilities were paired and assigned to one or the other program. Those subjects involved in the ordered training learned significantly better than those involved in the random training. The work conducted on space-filling visualizations is a continuation of this research with one key difference, that of using a verbal protocol analysis to suggest the difficult properties as well as the strategies used by high spatial subjects to solve the problems.

2.6 Chapter Summary

Overall, the aforementioned research investigated individual differences in visualization comprehension skills, the relationship between visualization comprehension skills and spatial abilities, and the relationship between visualization literacy and various spatial learning environments. In addition, these studies revealed the necessity and importance of understanding specific problems people have in comprehending visualizations in order to develop proper training methods.

This chapter, by reviewing related research on 3D visualizations, highlighted why this thesis is important and unique. It noted that because of the common usage of 3D visualizations in today’s world, people need basic visualization literacy skills. However, studies show that such skills are often lacking. Therefore, to solve this problem, the
chapter suggests either improving visualizations to make them easier to understand or training people to understand visualizations better. Unfortunately, how or why people have trouble in comprehending visualizations is not fully understood yet. The work so far has been limited with only a small amount of effort going into what visual characteristics make 3D visualizations difficult to comprehend and how to best develop visualization comprehension training modules. Thus, the work carried out in this thesis that looks at the strategies people use in solving cross section problems in space filling visualizations and the specific features of the visualizations which engender these strategies will serve as a unique and valuable contribution to this area of research.
Chapter 3

3. Generation of Slice Visualization Problems

3.1 Introduction

This chapter focuses entirely on the selection of stimuli (problem sets) to use with the subjects in this research. In order to run a verbal protocol study that will help in finding out what makes the variations in a 3D block visualization easy or hard, it is necessary to (1) collect a set of representative 3D block visualizations to use with our subjects, (2) vary this set of visualizations sufficiently to ensure that as wide a range of properties as possible is included, (3) develop a problem that subjects need to solve with the visualization and (4) order the visualization problems from easiest to hardest for presentation to subjects. The first task was tackled by looking for example visualizations in beginning textbooks in geology and earth science. The second task used geology features described in the textbooks to demonstrate each visualization’s variability and difficulty. The third task was borrowed from other studies of visualization comprehension [20] and asked subjects to draw an internal view of the visualization. The fourth task had experts and novices solve the visualization problems and rank order the problem set by difficulty. The rest of this chapter explains in detail how each of these tasks was carried out. The end result of this effort is a set of fifteen 3D block visualization problems ordered by increasing difficulty that will be shown to subjects in the experiment described in Chapter 4.
3.2 Collecting Sample Visualizations

A set of 3D block visualizations were generated from introductory Geology and Earth Science textbooks [29][30]. Since many of the drawings in these textbooks are rendered in color and since subjects will be asked to recreate portions of these drawings using pencil and paper, an artist was hired to redraw these figures in black and white using textures to represent the colors, e.g., dots, stripes, crosshatching, etc. The figures were also modified somewhat to make it easier for subjects to redraw a portion of the visualization in the visualization comprehension test given to them. This was done to keep drawing skills from interfering with the primary task of comprehension. The geology researcher roughly ordered the visualizations in order of comprehension difficulty. A total of 35 figures were created for this task. These are shown in Appendix A1. Index of Preliminary Experiment Diagrams. An example of one of the easier visualizations and one of the more difficult ones are shown in Figure 3.

![Figure 3 Example Visualizations](image)

(a) (b)

Figure 3 Example Visualizations. 3 (a) is an example of an easier visualization while 3 (b) is an example of a more difficult visualization

3.3 Categorizing Visualizations by Geological Properties

The consulting geology researcher also labeled five properties of the visualizations as they are used in the field of Geology. These properties were assigned
values ranging from 0 to 2 depending on the extent to which the property was exhibited. Then, the values were added to form an index of difficulty for each of the 35 block visualizations. The property values and the calculated index of difficulties are shown in Appendix A1 along with the figures. Each of the properties is illustrated and explained below.

1. **Direction of Layer Tilting in Relation to Plane of Presentation**

   0 = no tilting
   1 = tilted only in x-z plane or y-z plane
   2 = tilted in both x-z and yz-plane

![Figure 4 Examples of the Direction of Layer Tilting Property.](image)

- (a) is flat layers with no tilting and thus, gets a score of 0.
- (b) has layers tilted at an angle from the x-y plane and thus, gets a score of 1.
- (c) has layers tilted at an angle from the x-z plane and also gets a score of 1.
- (d) has layers that are tilted both in the x-y and the x-z planes, thus receiving a score of 2.

A block visualization has planes of presentation to the viewer, that is, the left side of the block is considered parallel to the y-z plane and the right side of the block is parallel to the x-z plane. If layers within the visualization are not parallel to these planes, it is believed that they are more difficult for the viewer to visualize. In addition, layers that are tilted in both the x-z and y-z planes are considered even more difficult to comprehend than layers that only tilt in one of the planes. The index of difficulty assignment for this property was therefore given a 0 for block visualizations with no layers tilted and 1 for
block visualizations with layers that have tilting only in the x-y or the y-z plane. A 2 is assigned for block visualizations with layers that have tilting in both x-z and y-z planes. Because these geologic layers can also appear to tilt because they are part of folds, if this is evident in such a visualization, the tilting is not scored as a difficulty. There are also instances where layers tilt in one direction and then form a mirror image of this tilt in a different direction. This is considered a fold. In addition, some visualizations have embedded figures that also tilt. The tilt direction is not counted for these figures.

2. Fold

\[0 = \text{no fold}\]
\[1 = \text{presence of a fold}\]

![Figure 5 Examples of diagrams with geologic folds](image)

A fold in geology is what happens when one or more of originally flat and planar surfaces are bent and curved as a result of permanent deformation. Folds also cause the index of difficulty of a block diagram to be greater because the layers will no longer be straight and will be more difficult to follow. In this study, a fold is described as a deformed (not flat) top surface. The layers in a fold are not flat but undulate or change in a regular fashion along the y-z plane. The index of difficulty assignment for this property will be 0 for block diagrams that do not have curved layers, and 1 for block diagrams that do have curved layers.
3. **Fault**

0 = no fault

1 = fault

Figure 6 An example of a fault. The index of difficulty is calculated for each side of the fault and a value of 1 is assigned for the presence of each fault.

A fault in geology is a planar discontinuity or fracture in a volume of material that has significant displacement. Faults cause more difficulty in comprehending block visualizations because there is a discontinuity in the layers within the block visualization. The index of difficulty assignment for this property will be 0 for block diagrams with no faults, and 1 for each fault within a block visualization. The scores for each side of a fault in a block visualization will be calculated separately and then added together to obtain the total score for the entire block visualization.

4. **Embedded Object**

0 = none

1 = an embedded object exists
Figure 7 An example of an embedded object in a block visualization. This visualization will receive a score of 1 for its embedded figure property.

An embedded object is an object that has been surrounded by other standard geologic figures. It is believed that embedded objects within block visualizations cause more difficulty in the comprehension of the block visualization because embedded objects are hard to mentally imagine within the internals of the block because the object is surrounded by the other layers of the block visualization. The index of difficulty assignment for this property will be 0 for block visualizations that have no embedded objects and 1 for each embedded object within a block visualizations.

Number of layers
0 = less or equal to 4
1 = greater than 4
Figure 8 An example of a block visualization that has six layers. It will therefore receive a score of 1 for the number of layers property.

The number of layers of a block diagram affect its index of difficulty because the more layers a block diagram has, the more difficult it is to retain all of the layer information as an individual is trying to understand the internal properties of a block diagram. The index of difficulty assignment for this property will be 0 for block diagrams with 4 or less and 1 for greater than 4 layers. This was a relatively arbitrary decision, in part, because few of the block visualizations in the problems being used had more than six layers. It is not clear if these two additional layers will make a difference.

For each of the thirty-five figures that were selected, an index of difficulty was then calculated by adding each of the assigned property values that occurred for the figure and summing up the result for all such properties found in each figure. Appendix A1 lists the count or value for each geologic property and the index of difficulty calculated for each figure. The figures in Appendix A1 are shown in the order of difficulty as originally assigned by the research group. As can be seen, some indices of difficulty place some figures in a different location than that originally assigned. It was also seen that although the index of difficulty served as a first level representation of how
hard the visualization problems were to comprehend, there was considerable interaction between the properties that contributed to problem difficulty, a feature not captured by the linear and independent index of difficulty measures. Nevertheless, the indices of difficulty served as a first level scoring of problem difficulty. To determine how well this scoring worked, a visualization problem was created and applied to each of the 35 visualizations that were drawn from the geology textbooks. Experts were then asked to solve these problems and evaluate the problem’s solution difficulty. Their evaluation was compared to the indices of difficulty and used to select and order a set of representative visualization problems to be given to medium to low spatial ability subjects for an analysis of the types of difficulties they had with the problems. This visualization problem type, slice visualization, used in the expert and novice studies is explained in the next section.

3.4 Generating the Slice Visualization Problem

The previous section describes how the difficulty ratings of individual block diagrams were assigned based on their geologic properties. While this may be useful in estimating the difficulty of block diagrams, it does not provide the information necessary to determine how individuals understand the internal structure of these visualizations. Alde describes Visual Penetration Ability or VPA which is the ability to create a mental image of an object and perform mental manipulations on it such as rotations and translation [20]. Designing a visualization test that can assess the ability of individuals to understand what is going on inside a particular block diagram can aid in the determination of what exactly about the block diagram may make the diagram more
difficult to understand. The properties of the diagrams that cause this difficulty can then be extracted out and correlated to difficulty in comprehension.

The visualization test should be designed to help reveal what people understand about the internal properties of a block diagram. A problem type, the “slice visualization,” was created to determine this. Slice visualizations are block visualizations that have a cross-section slice that indicates a cut through the block. The slices that cut through the block diagrams can occur at various angles and in various locations within the block. The different angles and locations may lead to varying degrees of difficulties in comprehending the resulting slice. Subjects are asked to imagine what the layer that the slice cuts through looks like and to draw the resulting cross-sectional slice. This type of problem can help reveal how much an individual understands about the interior properties of a block since individuals have to be able to picture the slice correctly to draw it accurately. By designing the test to assess the ability of an individual to understand a particular visualization, the properties of the visualization can then be dissected to determine what exactly about the diagram makes it difficult. An example of a slice visualization is shown below in Figure 9.

![Figure 9 Example of a slice visualization problem.](image)
3.5. Experiment on Rank Ordering the Visualization Problems

The plan for the rest of the research is to videotape low to medium spatial subjects solving space-filling visualization problems and to analyze the videotapes for the purpose of generating hypotheses about what features or properties of the visualizations give the subjects difficulties. The analysis will attempt to understand the comments the subjects make as they try to solve the problems as well as the sketching, paper moving and gestures made on, with and about the problems. It is important, however, to select an appropriate set of problems for the subjects. These problems must be representative of a wide range of space-filling visualizations in order to ensure that the properties found to cause subjects difficulty cover the broadest possible spectrum of properties. This was done by selecting a wide range of block visualizations from geology textbooks with the help of a geologist. The consulting geologist selected visualizations that ranged from trivial to extremely difficult and ordered them accordingly. However, it was important to test this ordering on non-geologists who might see the problems differently. In particular, it was important to have an easy to hard ordering on the problems used for our videotaping study. If the subjects work on the hardest problems first, they might not be able to solve these and give up attempting to solve all the problems selected for the study. Subjects are also likely to get better at solving the problems as they progress through them because they will learn strategies for solving the problems. If they learn such strategies on the harder problems, it may not be possible to observe difficulties the subjects might have with the easier problems. In this case, important and useful information could be lost. Therefore, a rank order study was carried out on the 35 visualizations selected from the Geology textbooks.
Each subject received a copy of the 35 visualization problems which consisted of a different problem on each sheet of paper. Each sheet had a block diagram visualization sliced by a slicing plane followed by white space in which to draw the corresponding cross-section. The 35 slice visualization problems can be found in Appendix A1. The subjects were asked to draw the cross-sections in the order in which the problems were presented taking whatever time was necessary to create the drawing. A written sheet of instructions that were given to each participant is shown in Appendix A2. For each slice visualization problem, participants were asked to perform the following tasks: (1) draw what they believed to be an accurate rendition of the cross-section that would appear on the slicing plane; (2) record how much time it took to solve the problem and complete the drawing; (3) record on a Likert scale from 1 to 7 how difficult they found the problem to be with 1 being very easy and 7, very difficult and (4) rank order all of the problems when they finished solving all of the visualizations from easiest to most difficult.

The participants used in this rank ordering study experiment were a geologist, a psychologist, two computer scientists, a sociologist, an astronomer, and an information science specialist. All had advanced degrees in their fields. Although spatial ability was not tested in this group of individuals, it could be assumed given the various backgrounds that most of the participants had relatively high spatial ability although that some, e.g., the astronomer and the geologist, would be likely to score the highest in these skills.

### 3.6 Results from the Rank Order Study

The first order of business in examining the results from the rank ordering study was to determine the reliability and validity of the data collected from the seven experts
Reliability is the consistency of your measurement, or the degree to which an instrument measures the same way each time it is used under the same condition with the same subjects. In short, it is the repeatability of your measurement. A measure is considered reliable if a person's score on the same test given twice is similar. In the ranking study, time to solve problems and self-assessment of how difficult the problem was were measured. If the experts correlated highly on these two measures, this was used as a measure of reliability, that is, the problems were similarly difficult and easy across all participants.

Validity is a measure of how well the data collected correlates with what the study was intended to measure. This is usually captured by collecting a second known value that also represents the intended value or concept and calculating the correlation between each of the measures. The rank order study was designed to determine the ordering of the cross section problems in terms of their difficulty. Each individual’s self assessment was captured. Since the time to solve a problem can be argued to also represent a problem’s difficulty, a correlation between this and the rank orderings of each study participant should indicate the validity of the study. The Likert scale assessment of problem difficulty is a second measure that can also be used in assessing validity primarily because its own efficacy has had an extensive amount of testing and evaluation.

3.6.1 Determining the Reliability of the Rank Order Data

A Pearson rank order correlation was computed between the seven subjects’ self-reported length of time (in seconds) taken to solve problems. Among the 35 problems, 2 problems with missing values were excluded from the analyses. Correlation analyses
show that the correlations were statistically significant (p < 0.05) and all were greater than or equal to .40. Thus, the length of time taken in solving problems was positively correlated between the subjects indicating that problem difficulty was similar across the subjects. The results are presented in Table 1.

Table 1 Pearson Correlation among Subjects on Time Taken to Solve Slice Visualization Problems (N=33)

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*p < .05. **p < .01.

Pearson rank order correlations were also computed between the seven subjects’ self-reported values on the difficulty of the problems that were rated on a 7-point Likert scale ranging from 1 (very easy) to 7 (very difficult). Among 35 problems, 6 problems with missing values were excluded from the analysis. The results of this correlation analysis presented in Table 2 show that all correlations were statistically significant (p < 0.01) and were greater than or equal to .73. Figure 10 is the scatter plot matrix that visually represents the relationship between subjects’ ratings. Thus, subjects’ ratings on the difficulty of problems were highly correlated and statistically significant. This and the
time to solve correlations indicate that the subject’s performance is highly reliable and that these ratings can be used in categorizing the difficulty of the problems.

Table 2 Pearson Correlations among Subjects' Ratings on Difficulty of the Problems (N=29)

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** p < .01.

Figure 10 Correlation among subjects' ratings on difficulty of the problems

3.6.2 Determining the Validity of the Rank Order Data

A Pearson rank order correlation was also computed between the time taken to solve problems (measured in seconds) and the Likert ratings of problem difficulty. The
results show that time taken to solve problems and ratings of problems’ difficulty was highly correlated, \( r (239) = .76, \ p < .01 \). Figure 11 is the scatter plot that visually displays the relationship between time and ratings of problems’ difficulty. This additional high correlation between the time and perceived difficulty measures provides support to the argument that the self report of the subjects on problem difficulty has strong validity.

![Figure 11 Correlation between time and ratings on difficulty of the problems](image)

**3.6.2 Determining the Problem Difficulty from the Rank Order Study**

Pearson rank order correlations were computed among six subjects’ self-reported ranking of the difficulty of 35 problems that were ranked from 1 (most easy) to 35 (most difficult). Correlation analyses show that all correlations between subjects were statistically significant (\( p < 0.01 \)) and were greater than or equal to .79. Table 3 and Figure 12 display these results. The strong and significant correlations between the subjects both on the time to solve each problem and on the self assessed difficulty level of each problem indicates that the data collected from these experts was highly reliable.
In addition, because self assessed difficulty correlates highly and significantly with time to solve each problem, the study also suggests that our measures are valid, that is, that the self assessment variable of difficulty correlates highly with what would be expected behavior with problem solvers, i.e., that harder problems would take longer to solve. Thus, the final variable captured in this study, that is, the ranking of problem difficulty which is again self assessment data of how difficult experts viewed each problem can be considered to be both a reliable and valid measure. This data can now be used to help select and order problems for the next experiment on novice users.

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<td></td>
</tr>
<tr>
<td>S5</td>
<td>.82**</td>
<td>.82**</td>
<td>.79**</td>
<td>.83**</td>
<td></td>
<td></td>
</tr>
<tr>
<td>S6</td>
<td>.88**</td>
<td>.87**</td>
<td>.85**</td>
<td>.91**</td>
<td>.80**</td>
<td></td>
</tr>
</tbody>
</table>

** p < .01.
Overall, there was general agreement among subjects as to which problems were really easy and which problems were very difficult (impossible). What is of interest in selecting a set of problems for the videotaping study is both those problems that were not consistently ranked across participants and those that were not. In the case of consistent ranking, it can be assumed that the problem’s ranking caused no difficulties and that if we select the problem as one to use in the study, where to place it can be guided by the rankings. However, the inconsistent rankings are also of interest because it indicates that there is some feature or property which some participants had experience in handling and others did not. Thus, these problems were also important to consider for inclusion in the videotaping study which is designed to determine what types of visualization properties might be causing comprehension difficulties.
Figures 13-16 shows a visual comparison of the rankings; colored lines are used to track the ranking of individual problems. Flatter lines imply more agreement on a problem’s difficulty.

Figure 13 A graphical comparison of rankings for first 10 problems solved by the subjects
Figure 14 A graphical comparison of rankings for problems 11-20 solved by the subjects
Figure 15 A graphical comparison of rankings for problems 21-30 solved by the subjects
Figure 16 A graphical comparison of rankings for problems 31-35 solved by the subjects

Problems 1, 2 and 3 were consistently ranked as easy problems. Problems 4-13 followed with consistent rankings that categorized them as easy-medium. However, problems 10 and 13 were also scored as medium by some of the participants. The next categorization is problems 14-21 although problems 18 and 21 were considered easy-medium by at least two participants. This category was labeled medium. The next category contains problems 22-29 which were medium – difficult. Both problems 28 and 29 were also ranked as difficult by at least some participants. Finally, problems 30-35 were indicated by most participants to be difficult although the last two participants
rated them much easier than problems 28 and 29. Problems 31 and 34 had high variance in their rankings.

As a strategy for selecting 15 problems for the videotaping study, three problems were chosen from each category (2 problems with consistent rankings and 1 with inconsistent rankings). Table 4 below illustrates the problem numbers and their categorizations.

<table>
<thead>
<tr>
<th>Level of Difficulty</th>
<th>Consistent Problems</th>
<th>Inconsistent Problems</th>
</tr>
</thead>
<tbody>
<tr>
<td>Easy</td>
<td>1, 2, 3</td>
<td>None</td>
</tr>
<tr>
<td>Easy-Medium</td>
<td>4, 5, 6, 7, 8, 9, 11, 12</td>
<td>10, 13</td>
</tr>
<tr>
<td>Medium</td>
<td>14, 15, 16, 17, 19, 20</td>
<td>18, 21</td>
</tr>
<tr>
<td>Medium Difficult</td>
<td>22, 23, 24, 25, 26, 27</td>
<td>28, 29</td>
</tr>
<tr>
<td>Difficult</td>
<td>30, 32, 33, 35</td>
<td>31, 34</td>
</tr>
</tbody>
</table>

Table 4 The difficulty categories created by the rank order study. These categories were used to create the set of problems used in the videotaping study (described next).

It was decided to use the easy problems (1, 2 and 3) as practice examples in the study. The other problems were selected as indicated, i.e., three from each category in increasing order of difficulty with one inconsistent problem each. However, it was found in trial runs of the videotaping experiment that the Medium Difficult and Difficult
problems were too hard for the subjects. Therefore, four similar medium problems were created to replace these problems with the final problem set only containing two Medium Difficult and one Difficult problem. Table 5 lists the final set of fifteen problems that were used for the videotaping study along with their solutions. Problem 10 (a Medium Difficult Problem) is out of order and should have been placed below Problem 12 (the last of the Medium Problems). This problem was put in this position because none of the trial subjects were able to get any further than Problem 10 and it was felt that at least one difficult problem be presented to each of the subjects in the study.

It should be noted that no indices of difficulty or visual properties of the visualizations were used to create the final list of problems to use. This is important because the intent of the study is to determine what properties in these visualizations might be causing problems. Because there will naturally be learning in the experiment being conducted, organizing the problems based on visual properties might bias the results, that is, an important and difficult visual property might be overlooked in the videotape analysis because the property was grouped in such a way that it was learned and that learning automatically used to solve the next problem, and so on. It was therefore important to only organize the problems based on perceived difficulty only.

<table>
<thead>
<tr>
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<tbody>
<tr>
<td>Example 1</td>
<td><img src="image1.png" alt="Image" /></td>
<td><img src="image2.png" alt="Image" /></td>
</tr>
<tr>
<td>1 - Easy</td>
<td><img src="image3.png" alt="Image" /></td>
<td><img src="image4.png" alt="Image" /></td>
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<tr>
<td>--------------------------------------------------</td>
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<tr>
<td>Example 2</td>
<td><img src="image1.png" alt="Image" /></td>
<td><img src="image2.png" alt="Image" /></td>
</tr>
<tr>
<td>3 - Easy</td>
<td><img src="image3.png" alt="Image" /></td>
<td><img src="image4.png" alt="Image" /></td>
</tr>
</tbody>
</table>

| Example 3                                        | ![Image](image5.png) | ![Image](image6.png) |
| 2 - Easy                                         | ![Image](image7.png) | ![Image](image8.png) |

| 1                                               | ![Image](image9.png) | ![Image](image10.png) |
| 7 – Easy Medium                                  | ![Image](image11.png) | ![Image](image12.png) |

| 2                                               | ![Image](image13.png) | ![Image](image14.png) |
| 4 – Easy Medium                                  | ![Image](image15.png) | ![Image](image16.png) |

<p>| 3                                               | <img src="image17.png" alt="Image" /> | <img src="image18.png" alt="Image" /> |</p>
<table>
<thead>
<tr>
<th>9 – Easy Medium</th>
<th><img src="image19.png" alt="Image" /></th>
<th><img src="image20.png" alt="Image" /></th>
</tr>
</thead>
<tbody>
<tr>
<td>4</td>
<td><img src="image1.png" alt="Image" /></td>
<td><img src="image2.png" alt="Image" /></td>
</tr>
<tr>
<td>19 - Medium</td>
<td><img src="image3.png" alt="Image" /></td>
<td><img src="image4.png" alt="Image" /></td>
</tr>
<tr>
<td>5</td>
<td><img src="image5.png" alt="Image" /></td>
<td><img src="image6.png" alt="Image" /></td>
</tr>
<tr>
<td>13 – Easy Medium, Inconsistent</td>
<td><img src="image7.png" alt="Image" /></td>
<td><img src="image8.png" alt="Image" /></td>
</tr>
<tr>
<td>6</td>
<td><img src="image9.png" alt="Image" /></td>
<td><img src="image10.png" alt="Image" /></td>
</tr>
<tr>
<td>15 - Medium</td>
<td><img src="image11.png" alt="Image" /></td>
<td><img src="image12.png" alt="Image" /></td>
</tr>
<tr>
<td>7</td>
<td><img src="image13.png" alt="Image" /></td>
<td><img src="image14.png" alt="Image" /></td>
</tr>
<tr>
<td>Added to create Medium Problem</td>
<td><img src="image15.png" alt="Image" /></td>
<td><img src="image16.png" alt="Image" /></td>
</tr>
<tr>
<td>8</td>
<td><img src="image17.png" alt="Image" /></td>
<td><img src="image18.png" alt="Image" /></td>
</tr>
<tr>
<td>Added to create Medium Problem</td>
<td><img src="image19.png" alt="Image" /></td>
<td><img src="image20.png" alt="Image" /></td>
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<tr>
<td>---------------------------------------------</td>
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</tr>
<tr>
<td>9</td>
<td>Added to create Medium Problem</td>
<td><img src="image1.png" alt="Diagram" /></td>
</tr>
<tr>
<td>10</td>
<td>26 – Medium Difficult</td>
<td><img src="image2.png" alt="Diagram" /></td>
</tr>
<tr>
<td>11</td>
<td>Added to create Medium Problem</td>
<td><img src="image3.png" alt="Diagram" /></td>
</tr>
<tr>
<td>12</td>
<td>21 – Medium</td>
<td><img src="image4.png" alt="Diagram" /></td>
</tr>
<tr>
<td>13</td>
<td>26 – Medium Difficult</td>
<td><img src="image5.png" alt="Diagram" /></td>
</tr>
</tbody>
</table>
Table 5 The set of problems selected for the videotaping study. Column 1 contains two values, first, the problem number for the problems in the videotaping study and second, the problem number and category of this same problem in the rank order study.

3.8 Chapter Conclusion

The rank order study was run to both select a meaningful distribution (easy to difficult) of space visualization problems to give to subjects in the videotape experiment described in Chapter 4 and to order these problems from easy to difficult so that subjects would gradually advance their comprehension of the problems and solution difficulties as they advanced through the problems presented to them in the experiment. Because asking participants to rank order a set of thirty-five space visualization problems has the potential of being a task that is too difficult to do because (a) of the large variations in problem types and (b) of the large number of items that require comparisons and sorting,
the study has the potential of generating highly erroneous data. Therefore, both reliability and validity data were collected through additional measures, i.e., assessment of difficulty for each individual problem and time to solve each problem. It was found that both the reliability and validity were significant and high. In addition, the correlation among participants in the study was also very high.

The rank ordering was used to select 3 training and 15 test problems for the videotaping study which were grouped from easy to difficult. Additional medium problems needed to be added because trial subjects had too much trouble with the difficult problems. Now that the experiment problem set has been created and verified, the next chapter introduces the experiment that will be used to uncover properties of the space visualizations that make them hard to understand.
Chapter 4

4. The Videotape Experiment

4.1 Introduction

The previous chapter described a quick study conducted among the researchers engaged in the visualization literacy project that was designed to get some understanding about what cross section problems were easy for individuals to solve and what others were difficult. This knowledge was then used to develop an exploratory experiment in which subjects were given a set of cross-section problems that began with those that were easy to solve and preceded to those that became progressively harder. The purpose of the experiment was to help researchers in designing a training program to improve an individual’s comprehension of 3D visualizations. The experiment is an exploratory study asking individuals to speak aloud while solving progressively harder cross section visualization problems. Videotapes of these solutions were analyzed to determine what properties of the visualizations were causing difficulties and what strategies the individuals were used to overcome these difficulties. This thesis focuses on visualization property difficulties with the intent of designing training strategies that provide stepwise solutions to illustrate techniques for understanding the behavior of the visualization properties causing comprehension difficulties. The rest of this chapter describes the experiment in detail.
4.2 3D block visualizations

The visualizations used in this study are black and white, hand-drawn, 2D representations of 3D blocks that are shown on paper. These visualizations contain different patterns to represent layers and may contain layers at different angles and in different shapes. As described in the previous chapter, the 3D block visualizations have slices drawn through them that are represented by the letters A, B, C and D connected by a dotted line. The blocks contain many different properties designed to represent features of visualizations that typical space-filling visualizations may contain. The figures used in this experiment are shown in a summary listing in Appendix B1. A more detailed analysis of the figures can be found in Appendix B2.

4.3 Experiment setup

Subjects for this experiment were found by posting notices on the university campus and by recruitment in classes. Subjects were paid $15 for this experiment that lasted approximately 1 hour. The signup sheet advertising the experiment can be found in Appendix C1.

4.4 The experiment

Subjects were seated at a table in a quiet room and given a consent form to agree to participate in the study. The consent forms are shown in Appendix C3. Each subject was then given a basic spatial abilities test, the paper folding test. The subject was then given the training materials. The entire training sequence is shown in Appendix C2. The
subject was asked to read all of the instructions aloud. Following the training, the subject was then given the 3 practice problems and then the 15 experiment problems.

Subjects were given one hour to work through the experiment that involved solving up to 15 3D block visualizations problems. The problems were on paper and consisted of a 3D space-filling visualization with space below it for the subject to draw in. A virtual plane slices the visualizations into two pieces. Figure 17 is an example of this type of visualization. Subjects were asked to draw what the slicing plane looks like in the free space provided below each problem. After each problem, the subject would be able to see the solution to the problem he or she just completed. The ordering of the 15 problems was based on the rank ordering done in Chapter 3. The easiest problems were given first and the problems became progressively harder. The entire 15 problems are shown in Appendix B2.

![Figure 17 Example of visualization problem used in the experiment with its solution shown to the right.](image)

The subjects were requested to verbally express their thought process while solving the problem. Subjects were recorded by a video recorder which captured their drawing process and speech as they worked through the problems. Throughout the study, if the
subject stopped verbalizing they were gently reminded to continue thinking out loud. Subjects had multiple soft pencils for drawing their answers and a large eraser for making changes to their answers. After one hour, if the subject had not finished the entire problem set, the experiment was stopped and the subject debriefed on the purpose of the study. A copy of the debriefing statement can be found in Appendix C4. The subject was then thanked for his or her time and paid $15.

4.5 Chapter Summary

The aim of the Videotape experiment was to gather data that could be used to identify difficult properties of 3D block visualizations. The subjects were first given a training sequence so that they would understand the problems they were to solve. They were then given the experiment which consisted of 15 3D block visualizations problems that were designed to gather problem solving strategies. The subjects were recorded on video so that the properties of the visualizations causing difficulties could be captured along with the strategies the individuals used to overcome those difficulties. The next chapter presents an analysis of the videos that were captured in this experiment.
Chapter 5

5. Analysis of Results of Experiment

5.1 Introduction

The focus of the videotape experiment was to uncover the comprehension problems subjects had when they tried to solve the cross section visualization problems and relate these to the properties of the problem. Based on the videotape analyses, three main properties were found to make the drawing of the cross-sections harder: (1) The relation of the primary information plane to the planes of presentation; (2) The angle of the cutting plane in relation to the primary information plane; (3) And the number of faces needed from the diagram in order to understand the information presented and visualize the cross-section.

5.2 Definitions

The planes of presentation are defined as follows: Typically, the slice visualization problems are in block form or nearly block form. The front edge of the block is normally the center of the visualization with a left face, a right face and a top face being visible. This is shown in Figure 18. Next to the block is a coordinate system showing the x, y and z coordinates. The z – axis is parallel to the front edge of the block. The x – axis is parallel to the bottom right edge of this block and the y –axis is parallel to the bottom left edge. This coordinate system is called the planes of presentations of the block visualization with the x-y plane forming the bottom of the block, the x-z plane
forming the right face and the y-z plane, the left face. One can imagine this by thinking of placing the visualization in a square room such that its sides are parallel to as many walls, floors and ceilings as possible. The coordinate system of this room would then be the coordinate system that a viewer of the visualization might assume when looking at the visualization and trying to imagine what is happening internally inside the visualization based on the visual cues given on the sides of the 3D diagram. The planes of presentation also represent how the individual perceiving the visualization orients him or herself in relation to the problem. This is similar to the typical Cartesian coordinate system that individuals use to navigate through cities, i.e., they see the cities as north-south and east-west sets of streets that form a grid. Even if a city is organized at an angle to the NS and EW arrangement, people who live in the city will talk of the streets as running north-south and east-west to help their orientation and navigation. So it is, also with the visualization problems. The squareness of block visualization automatically sets up the planes of orientation for thinking about and viewing the visualization.

Figure 18 Block shown with x-y-z coordinate system
The primary information plane in the visualization is defined as follows. In each visualization used in the videotape study, layers were presented such that a plane could be drawn that is parallel to the information displayed in the layers. This plane would represent the primary information plane. Figure 19 illustrates such an arrangement where the primary information plane is approximately parallel to the bottom side of the visualization or the x-y plane of presentation.

![Diagram of a visualization with layers parallel to the x-y plane of presentation.](image)

**Figure 19** An example visualization in which the primary information plane is approximately parallel to the x-y plane of presentation.

Figures 20 and 21 present examples of the three properties identified. Figure 20(a) has a set of layers (as can be seen by viewing the right face of the block) that are not parallel or perpendicular to any of the block faces. As such, the primary information plane is at an angle to the planes of presentation, and thus, more difficult for subjects. In Figure 20(b), the cutting plane is nearly parallel to the layers in the left face of the block making it more difficult than Figure 20(c) in which the cutting plane is perpendicular to the primary information (the parallel layers).

### 5.3 Results

Most of the subjects in the study exhibited more difficulties with cutting planes parallel to the primary information. They felt “lost,” and it was impossible for 10 of them to complete the problems with this property. Although in Figure 20(a) participants could use the front face of the block to visualize most of the cross-section, many of them became confused as was stated by subject 4: “I started with this one [indicating one of the
layers that crossed the cutting-plane), but this really confused me, so then I started to look at this other one [pointing at the white layer], but I couldn’t visualize well, so I had to block the bottom of the figure”.

![Figure 20](image)

**Figure 20.** Figure 20(b) and 20(c) are examples of problems in which the angle of the cutting plane is perpendicular to the primary information plane, whereas in figure 20(a) it is at an angle to the primary information plane making the problem more difficult. The problem in 20(b) is also made more difficult because there are two primary information planes, one illustrated on the right face of the visualization and one on the left face. This complicates the problem for the viewer who needs to use both planes to determine the correct answer.

Figure 21 illustrates property 3 in which the number of faces the subjects need to consider in order to visualize the cross-section has increased. Consistent with previous research, needing to use information from multiple faces takes more working memory to encode. This often occurs when more complex objects are embedded in the blocks [2]. We found that as more faces were needed to visualize a cross-section, the more difficult it became for participants to infer the correct answer. Some of the impressions of subject 8 trying to solve the problem illustrated in Figure 21(c) reflects this difficulty: “I couldn't do everything at once, I couldn’t see everything so I had to break it in small pieces in order to go step by step, approaching to each part differently, but the problem was the arch since I couldn't see it in an angle.”

![Figure 21](image)

**Figure 21.** Figure 21(a) is a simple problem that requires considering only the front face to solve the cross-section problem. 21(b) is the solution to the problem. Figure 21(c) reflects a more complex problem that requires considering the two faces of the diagram to solve the cross-section problem.
Figure 21(d) is the solution to the problem. The second face in 21(a) may be used to add the correct layer thickness details for drawing the cross section but it is not needed to understand what the cross section should look like.

We also found that individuals have preferred planes of presentation that make problems harder when violated. This is another version of property 1. Consider flipping Figure 21(a) forwards so that its right side is on the bottom. This becomes a more difficult problem to solve as subjects expect layers such as in those pictures found in geology textbooks to be horizontal.

5.4 Suggested Training Mechanisms

Based on the difficulties subjects had with visualization properties that were neither parallel or orthogonal to an imagined coordinate system implied by the visualization diagram, a number of training problem sequences can be used to help individuals re-orient their imaging to accommodate these properties and learn how to effectively form mental models of their internal behaviors. The following paragraphs describe and illustrate with diagrams a number of these sequences.

When the cross section planes were not parallel or perpendicular to the planes of presentation, this caused significant problems. Subjects in the videotape study solved such problems by assuming that the cross section planes were parallel, stated such and even hand sketched cross sections that were parallel. The suggested training sequence is to begin with a parallel cross section plane problem on a simple block visualization and then proceed to tilt it progressively at more and more of an angle for subsequent problems. Subjects will then learn that the solution is a somewhat skewed representation of the same solution with the parallel cross section. The problem set sequence and
solutions in shown in Figure 22 (a) to 22(e). This can be repeated with a more complex block visualization having multiple layers.

![Image](image_url)

Figure 22 The problem set sequence used to train individuals in how to visualize problems in which the cross section plane is not parallel to one of the planes of presentation along with the solution. 22(a) presents the problem with the cross section plane parallel to the y-z plane of presentation. 22(b) to 22(e) present problems in which the cross section plane moves progressively away from being parallel to this plane until it is actually perpendicular to it.

When the primary information plane was not parallel or perpendicular to the planes of presentation, this also caused subjects significant problems. They verbally suggested that they handled this problem by assuming that the primary information plane was parallel in problems were the deviation from parallel was not too large. As described in the previous paragraph, a sequence of training problems which begin with the primary information plane parallel to one of the planes of presentation and then progressively deviate from this parallelism by a larger and larger angle will be used to help an individual how to solve these types of problems. This sequence is shown in Figure 23 (a-c). A similar sequence will be used again with the angular deviation moving in opposite direction as that shown in Figure 23.
Figure 23 The problem set sequence used to train individuals in how to visualize problems in which the primary information plane is not parallel to one of the planes of presentation along with the solution. 23(a) presents the problem with the primary information plane parallel to the x-y plane of presentation. 23(b) to 23(c) present problems in which the primary information plane moves progressively away from being parallel to this plane until it is actually perpendicular to it.

It was also observed that subjects in the videotape study had difficulty with problems in which the primary plane of information was not a plane but an arc. Similar to the above training sequences, this arc can be created as only a slight arc and then extended to a more extreme arc to illustrate to individuals that the problem type and thus, solution is basically the same, just a more skewed version of the easier solution. This problem sequence is shown in Figure 24 (a-c) in which the arc gradually becomes a more extreme curve.

Figure 24 The problem set sequence used to train individuals in how to visualize problems in which the primary information plane is not a plane but an arc. 24(a) presents the problem with the primary information plane being a flat plane that is parallel to the x-y plane of presentation. 24(b) to 24(c) present problems in which the primary information plane moves progressively away from being a plane to a curved arc with it finally nearly intersecting the top of the block visualization.

The above three problem set sequences are examples of a much larger set of training sequences that have been developed to address the problems subjects had with
the various problems they encountered in the videotape study. Their training effectiveness will need to be investigated in a future study, but the findings from the videotape study suggest that these methods will be very effective at helping individuals build the correct strategies for forming mental images of various block visualization problem types. Such training differs significantly from what has already been developed for students in Geology (e.g., the Geo3D program) which primarily uses blow apart diagrams that show how the individual layers inside of a block visualization form the visualization [4]. Although this helps individuals understand the continued symmetry they see on the outside surfaces of a block visualization, it does not help them with forming and abstracting solution strategies for different types of visualizations. This initial work suggests that the problem sequences suggested above are also necessary.

5.5 Conclusions

The key difference between the three findings uncovered in the videotape analysis and the difficulties listed for the visualization properties is one of viewer orientation in relation to the information being presented in the visualization. Because the visualization was a block visualization, it automatically set up a viewer orientation along the planes of presentation. However, when features in the visualization were not parallel or orthogonal to these planes, mentally picturing their behavior became more difficult. This may be because a typical viewer does not have much practice in looking at such information or simply because much of our visual training is in the orthogonal world. In addition, it is known from spatial ability tests, that individuals have difficulty in looking at a scene or object from a different orientation. Thus, whenever information or the slicing plane of a
visualization is better viewed from the back, top, etc. side, this creates a difficulty for those viewers that cannot place themselves in this new orientation. Slices that were not orthogonal to the planes of presentation also created more comprehension problems, the more so when they sliced a visualization such that information presented in one plane of presentation (e.g., the right face of a block) needed to be integrated with information presented on another face (e.g., the left or top face of a block). This occurred frequently when slicing planes were not orthogonal to one of the planes of presentation.

Overall, it is not the varying geologic properties, such as folds, faults and number of layers that were found to cause the difficulties, but the presentations of these features that made them better viewed from a viewpoint other than the one presented to the user or presented features and cross-sections that were non-orthogonal to a user’s perceived coordinate system. It could be argued that these problems can be corrected by allowing a user to interact with and rotate visualizations, but this is not necessarily a good solution. Tversky demonstrate that animations for naïve users cause even more comprehension problems [31]. This thesis, instead, argues that naïve users can be readily trained in coping with the difficulties uncovered in these studies through a simple computer-based training program or even a data phone game application.

Finally, this chapter used these findings to suggest new types of training that gently lead individuals into developing strategies for solving various block visualization problems.
Chapter 6

6. Importance of Discoveries

Although a large number of studies have looked at visualizations and also how individuals comprehend them, the studies have been run either by individuals in the various disciplines that use such visualizations or by psychologists who are interested in how mental processes work. This leaves an important gap, in particular, in helping people to design better and more comprehensible visualizations. The people who study visualizations from their scientific discipline, e.g., Geology or Biology, inherently attach meaning to the various portions of the visualization such as “this represents a fault.” This confounds the 3D picture with the underlying science. In the case of Psychology, the properties of visualizations are not of interest, only the observed mental models that are postulated to be part of the comprehension strategy the subject is engaging in. Although useful, this also misses a key issue, that is, the small but significant property changes that cause a person to be unable to determine the relationships that are being portrayed with the visualization. In particular, much of the geometric information embedded in the design of these visualizations is omitted or ignored, e.g., oblique cuts of slicing planes are discussed but not in terms of their relationship to the block visualization and / or the planes of presentation of the block visualization. For a graphics person, such detail as knowing what the x-y, y-z and x-z planes are in relation to the overall visualization is very important. The everyday individual is not aware of these planes yet uses them to guide forming mental images of the internal behavior of a viewed visualization and these constrain their ability to reorient themselves around information that does not align with such planes.
What has been done in this thesis is a clarification in graphic’s terms exactly what properties cause people difficulty in 3D visualizations and then give an explanation in psychological terms as to why these properties are likely to cause problems. This combining of disciplines to begin to explain comprehension issues is one of key contributions of this work. A set of testable hypotheses has now been generated for a host of visualization properties that can now be tested in controlled experiments.

The limitations of the thesis are in the number of visualization problems that were examined (only 15) and in the number of subjects that were used in the studies (only 12). However, this work sets the path for more work in this area which is likely to uncover many more subtleties associated with visualization comprehension skills. For now, this research demonstrates a useful set of 3D block visualization properties that are to be avoided, if possible, and also mechanisms for providing computer-based education to improve individual visualization comprehension skills.
Chapter 7

7. Summary and Contributions

This thesis presented an approach to help determine what properties of 3D block visualizations make their comprehension difficult. By identifying these properties, visualization creation strategies can be designed that reduce difficult properties without compromising the amount of information presented by the visualizations. Training methods can also be designed to present visualizations in a way that can help improve the ability of individuals to comprehend difficult properties of visualizations. Using these methods to help develop education programs can lead to better visualization comprehension skills in the general population. This can lead to allowing more people to develop the visualizations skills necessary to successfully understand scientific and information visualizations that are necessary for success in many fields.

7.1 Summary of Results

The main finding in this study is that there are several identifiable properties that make 3D block visualizations difficult to comprehend. These visualization properties repeatably made it difficult for subjects to correctly identify the cross-section of the block diagrams that were presented, indicating that subjects could not comprehend the internal structure of the diagrams. Many of these properties also caused subjects to spend more time in trying to comprehend their effects on the internal structure of the diagrams.

These properties were discovered through detailed analysis of the strategies used by subjects to process 3D visualizations. Analysis of the verbal protocols of subjects
helped to identify when these strategies caused problems in visualization comprehension and what properties of figures lead to these incorrect visualization strategies.

The properties that were found to make visualizations difficult to comprehend are:

a. Properties that require the user to look at the visualization from a different orientation than that implied by the visualization presentation

b. Properties that present information in a way that is not orthogonal to the coordinate system implied by the visualization presentation

c. Properties that require the user to integrate information from multiple sources in the visualization in order to comprehend it.

There is evidence that mass training of properties can also help to improve the ability of people to understand how these properties affect the underlying internal structures of visualizations [13]. As demonstrated in several of the videos, subjects improved in their abilities to cope with difficult visualizations after seeing how properties in previous problems affected the cross-section solutions.

7.2 Contributions

The 3D block visualizations used in this study are very similar to actual visualizations used in many scientific fields. The visualization abilities necessary to process the information presented by these diagrams is similar. The work in this thesis suggests both how such visualizations can be made easier to understand, but more importantly, how visualization comprehension training can be developed for burgeoning scientists entering various fields.
7.3 Future Work

The plan is to extend this work beyond the current visualizations used and to build a website and/or data phone application that provides the visualization literacy training this thesis suggests should be built. Findings in previous studies can be taken into account when designing future studies that can maximize benefits for the participants. For example, Inkpen, McGrenere, Booth and Klawe found that there were gender differences in mouse-driven collaborative environments [31]. This information can be used to customize experiment design based on gender to help participants learn more from their training.
Appendix A. Preliminary Experiment

A1. Index of Preliminary Experiment Diagrams

Below is a table of the diagrams used in the preliminary experiment to rank order the visualization difficulties. These diagrams were used in the initial assessment of difficult properties and used to create a difficulty rating. The information gathered was used to create the problem set for the main study. Note that the ordering of this problem set was done by the research team that worked on this problem (4 people including an artist, a geologist, a computer scientist and a psychologist).

Table 6 Table of Preliminary Experiment Diagrams

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| 34         | ![Diagram](image3.png) | Direction of tilting: 1  
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A2. Rank Ordering Experiment Results

This section shows the results from the preliminary experiment. This information helps provide the background for the reasoning behind the analysis of the results of the experiment and the rationale behind the figures chosen for the primary study.

A2.1 Time to draw (in seconds)

This table shows the time to draw the cross-section for each problem. This information was used in Chapter 3 to create the Pearson Correlations among subjects on time taken in solving problems.

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Table 7 Table of time to draw for preliminary experiment

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### A2.2 Difficulty Ratings for Problems in Preliminary Study

This table shows the difficulty rating for each problem in the preliminary study. This information was used in Chapter 3 to create the Pearson Correlations among subjects’ rating on difficult of the problems. The ratings are from 1 to 7, with 1 being the least difficult, and 7 being the most difficult. The - indicates that the subject did not rate the problem.
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A2.3 Rank Ordering of Preliminary Problems

This table shows the rank ordering for each problem in the preliminary study. This information was used in Chapter 3 to create the Spearman Correlations among subjects on the ranking of problems’ difficulty. The problems are ranked with 1 being the easiest and 35 being the most difficult.

Note: subject 6 did not do the rank ordering

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Appendix B. Experiment Diagrams

B1. Experiment Diagrams Table

Below is a table of the diagrams used in the experiment to determine difficult properties in diagrams. Each diagram is listed with its number of layers, general angle of layers, and general angle of slice.

Table 10 Table of experiment diagrams

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</table>
B2. Description of diagrams

Below is a general description of each diagram used in the verbal protocol analysis experiment. This information is given to show and list in more detail the properties of the diagrams.

Problem 1

This diagram has 3 Layers that are curved at 0 degrees from the x-z plane. The slice is 30 degrees from the y-z plane and penetrates the center of the figure.

Problem 2
This diagram has 5 layers that are curved that are 0 degrees from the x-z plane. It has a slice that is about 20 degrees from the y-z plane that penetrates the center of the diagram.

Problem 3

This diagram has 4 layers that are straight and -45 degrees from the x-y plane. It has a slice that is 20 degrees from the x-y plane and penetrates the center of the block.

Problem 4
This diagram has 3 layers that are curved and are at around 45 degrees from the x-z plane. It has a slice that is at a 60 degrees from the x-z plane and penetrates the center of the block.

Problem 5

This diagram has 6 layers that are curved and at a 45 degree angle from the y-z plane. It has a slice that is at an angle of around 15 degrees from the x-z plane and penetrates the center of the block.
Problem 6

This problem has 4 curved layers that are at 0 degrees from the x-z axis. The slice is at 30 degrees angle from the x-z axis and penetrates the center of the block.

Problem 7

This block has 5 angled layers that are 15 degrees from the x-z plane. The angle is at around -45 degrees from the y-z plane and penetrates the center of the block.

Problem 8
This diagram has 4 v-shaped layers that are at a -20 and 20 degree angle from the y-z plane. It has a angled slice that is at a 30 degree angle from the x-z angle and penetrates the center of the block.

Problem 9

This has 5 v-shaped layers that are -30 and 30 degrees from the y-z plane. The slice is at a 15 degree angle from the x-z plane and penetrates the center of the block.

Problem 10
This block has 5 layers that are at an 45 degree angle from the y-z plane and 45 degrees from the x-y plane. The slice is at a 15 degree angle from the x-z plane and penetrates the center of the block.

Problem 11

This block has 6 angled layers that are at a 45 degree angle from the x-z and the y-z angles. It has a slice that is at a -30 degree angle from the y-z plane and penetrates the center of the block.

Problem 12
This block has 7 layers that are curved and at a 0 degree angle from the x-z plane. The slice is at a 30 degree angle from the x-y plane and penetrates the center of the block.

**Problem 13**

This block has 7 layers with 2 layers that are curved that are going in the z direction and 5 layers that are angled at a 45 degree angle from the x-y and y-z planes. The slice is at a -15 degree angle from the x-z plane and penetrates the center of the block.
Problem 14

This diagram has 11 layers, 5 that are v-shaped at -45 and 45 from the y-z plane and 6 layers that are 45 degrees from the x-y and y-x planes. The slice is at a 15 degree angle from the x-z plane and penetrates the center of the block diagram.
This diagram has 9 layers, 6 that are angled at a -60 degree angle from the y-z plane and -60 degrees from the x-y plane, and 3 that are curved that go along the z-axis. It has a slice that is at an -30 degree angle from the y-z plane and penetrates the center of the block.
Appendix C. Experiment Materials

C1. Sign-up flyer
Shown below is the sign-up flyer that was used in recruiting subjects for the study.

Attachment 3: Recruitment Notice

**Experiment Flyer**

Do you want to make $15 in one hour?

**How?:** Come to participate in our visualization study

**To sign up:** send an email to James Chiang, jjchiang@rutgers.edu

**Description of Study:**

This exploratory study aims to get a deeper understanding of how individuals visualize data. It is intended to develop a framework able to help researchers in the designing of a structured training program to improve individual’s comprehension of 3D visualizations. Participants will be given 15 slice visualizations and asked to draw what the slice looks like, based on the 3D space filling pictures shown on a paper.

Figure 25 Sign-up flyer
C2. Experiment Instructions

Shown below are the experiment instructions that were given during the experiment to give the subjects instructions on how to solve the 3D block visualizations problems. The subjects were instructed to read these instructions out loud.

3D Visualization Experiment Instructions

Please read these instructions out loud.

Thank you for agreeing to participate in our study. The purpose of the study is to see how people visualize and understand spaces that they cannot see but which are implied by the properties they can see. For example, in the following figure (Figure 1a), you cannot see the top of the circle, but if you were asked to draw the figure behind the bar, you would draw the entire circle as shown in Figure 1b.

Figure 1a Figure 1b

In this study, we are going to give you 15 figures and then ask you to draw the portion of the figure that you cannot see. We describe what the figures will look like in the following paragraphs.

The typical figure you will be viewing typically contains multiple layers. An example of such a figure is the three-dimensional box shown in Figure 2a. Such figures are composed of multiple layers. This is shown in Figure 2b.

Figure 2a Figure 2b

In this hidden space study, you will be given all sorts of shapes, not just cubes. The layers may not be horizontal but curved or at angles to each other and to the sides of the figures. You will be asked to imagine how they look inside these figures. The way in which we will ask you to imagine this is by cutting the figure in the middle at some place and asking you what the back side of the cut looks like. For example, if we cut the cube shown in Figure 2a in the middle (see Figure 3a), the face of the cut would look like that shown in Figure 3b.

Figure 25 Experiment instructions
Note that the cut is shown by the letters A, B, C (hidden) and D. The face from this cut as shown in Figure 3b is exactly the same as that on the front of the cube in Figure 3a because the layers that form the cube are at the same level throughout the cube. This would be true if any of the layers moved up or down vertically.

Sometimes we will not cut the cube vertically. This is shown for the same cube in our example in Figures 4a and 4b. Note that in Figure 4b we have stood the cut face upright. Also note that in Figure 4a, the letters A, B, C and D indicate the cut. We have shown the cut with dotted lines because parts of it are not truly visible.
C3. Subject consent form

Shown below is the subject consent form that subjects were given before participating in the experiment.

Figure 26 Subject consent form
C4. Debriefing statement

Shown below is the debriefing statement that subjects were provided with after participating in the experiment.

Debriefing Statement
3D VISUALIZATION EXPERIMENT

Thank you for your participation in the 3D Visualization Experiment.

This project studies the ability to understand visual representations of 3-dimensional information. In this experiment, we asked you to form a mental image of a 3-D object using common visualization techniques used in many science disciplines. These images present properties that are commonly found in the analysis of scientific data. Engineers, architects, medical doctors and other professionals use this type of visual representation.

We hypothesize that the improvement obtained from traditional training techniques varies depending on the initial level of skill in comprehension of spatial data and previous experiences. We expect that structured training (i.e., training that presents questions in increasing order of difficulty) will improve the skills of trainees with a wider range of spatial skills and backgrounds.

The findings will help us design better visualization techniques that accommodate a broader range of spatial abilities and skills.

After collecting data from all of the subjects (Number of correct answers, time to analyze and answer each question, questionnaire information and tests of general spatial ability), we will compare the results statistically to determine what factors affect visualization comprehension.

Remember that all the data collected in the experiment will be stored so as to preserve your privacy and confidentiality. Data from this experiment will be reported in summarized form only; your identity will not be revealed in any presentation or publication of this research.

We do not plan to disclose the results from the spatial ability cognitive tests. However, if you would like to know more about spatial abilities, or receive a copy of the paper once it has been published, please contact one of the experimenters and we will send to you the information.

Once again, thank you for your participation in this experiment.

Figure 27 Debriefing statement
Appendix D. Results of Experiment

D1. Subject 20110131_J_1 answers

Shown below is table of problems, their corresponding diagram, solution, and answer provided by subject 20110131_J_1.

Table 11 Table of answers for subject_20110131_J_1

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<th>Diagram</th>
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<th>Subject 20110131_J_1 answers</th>
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## D2. Subject 20110215_J_3 answers

Shown below is table of problems, their corresponding diagram, solution, and answer provided by subject 20110215_J_3. This subject only finished 6 of the problems.

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**D3. Subject 20110224_D_7 answers**

Shown below is table of problems, their corresponding diagram, solution, and answer provided by subject 20110224_D_7. This subject only finished 10 of the problems.

**Table 13 Table of answers for subject 20110224_D_7**

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D4. Subject 20110204_D_3 Answers

Shown below is table of problems, their corresponding diagram, solution, and answer provided by subject 20110204_D_3. This subject only finished 12 of the problems.

Table 14 Table of answers for subject 20110204_D_3

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<tr>
<th>Problem</th>
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References


