A COGNITION-BASED FRAMEWORK FOR THE DEVELOPMENT OF VISUALIZATION LITERACY

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ABSTRACT OF THE DISSERTATION

A Cognition-Based Framework for the Development of Visualization Literacy

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Dissertation Director: Prof. Deborah Silver and Prof. Marilyn Tremaine

Data visualizations are prevalent in scientific simulation, medicine, physical therapy, product design, manufacturing, weather predictions, simulations, and engineering. They are also used in information and scientific visualization for WWW exploration, document searching, and education. This pervasiveness makes it important to understand how we comprehend these visualizations, what comprehension difficulties can be expected in diverse populations, and which visual properties increase comprehension difficulty. This will enable us to create training methods that help people gain basic comprehension strategies and analytic skills for visualizations.

The goal of this dissertation is to define an approach that can be used to determine the factors that make a visualization difficult to comprehend by certain individuals. This information is then used to test if training using this information helps individuals develop new and workable strategies for visualization analysis.

In this dissertation we present an approach that is designed as a series of steps designed (1) to determine what cognitive abilities are correlated with comprehension of the visualization, (2) to identify visual properties that make a basic visualization difficult to comprehend and (3) to measure the effect of basic incremental training using these visual properties.

Acknowledgements

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Dedication

To my family.

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Chapter 1
Introduction

Visual representations of physical and abstract data are fundamental aids in problem solving and knowledge development processes. Representations such as maps, anatomical illustrations and other representations of physical phenomenon were developed by early civilizations and refined over the centuries. The use of computers gave birth to visual representation of abstract data such as financial information and dramatically increased the amount and complexity of the data shown in the visualization. The use of such visual representations was limited to highly specialized workers or individuals working on academic and military settings. However, the wide spread use of computers, the advances in graphics hardware and software, and the ubiquity of the Internet has taken the nature and use of visual representations in a new direction. Computer-based representations are called simply *visualizations*. The term visualization also refers to the cognitive process of creating a mental image based on visual information. In this dissertation, the term visualization will be used, in singular and plural form, to refer to both the visual representations and the visualization process. The meaning of the term depends of the context in which the word is used.

There is a large diversity of visualizations. The way in which data is represented is partially based on the dimensionality and the scale of data, as can be seen in Figure 1.1. Dimensionality refers to the complexity of the data in terms of the number of parameters that define each data element and scale describes the amount of data elements. Some visualization techniques specialized on representing large scale data where each data element has a relatively simple representation. As shown in Figure 1.1, visualizations of flow simulations [80] present large amounts of data where each element has a value (i.e., color) and a position in space. Other visualizations specialized on displaying data with where the data elements have complex structures and relationships. For instance, the CiteSpace visualization [15] presents complex networks

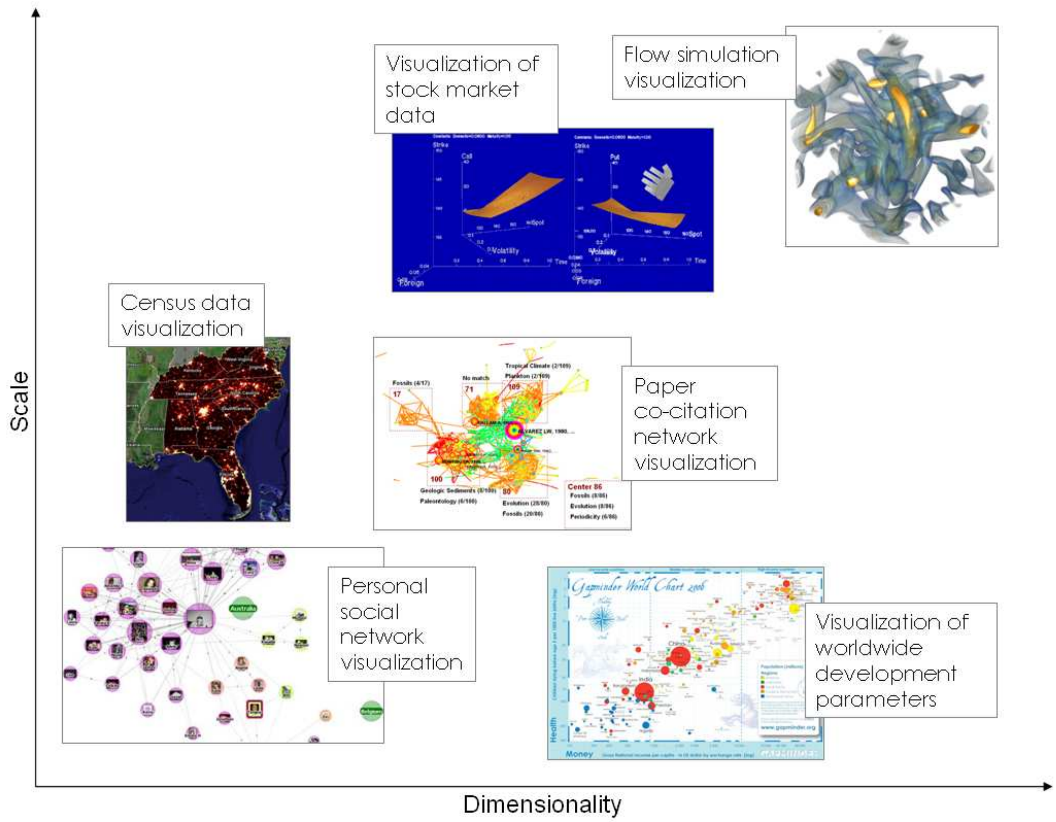


Figure 1.1: Examples of how the scale and dimensionality of data contributes to diversity of visualizations.

of co-citations in digital libraries. Finally, visualizations such as the ones applied to the stock market by Feiner [29] presents relatively large volumes of complex data elements. Dimensionality, space usage and enphasis of particular data properties are also factors that visualization designers employ to illustrate relationships between elements in the visualization. Figure 1.2 presents example visualizations created to represent hierarchical data.

The group of visualization users has expanded from a group of highly-trained individuals that once was. For many of today's professions, especially those related to cyberinfrastructure, analyzing high dimensional data is a crucial skill. Most professions take advantage of computers which transform and display data so that a person can better view the relationships between the items of interest. Educators use static and interactive visualizations to facilitate the comprehension of concepts at introductory levels in fields such as geoscience [48], biology [31] and mathematics [4]. Data of public interest such as weather updates and census information is commonly presented using visualizations. Moreover, the availability of visualizations on the

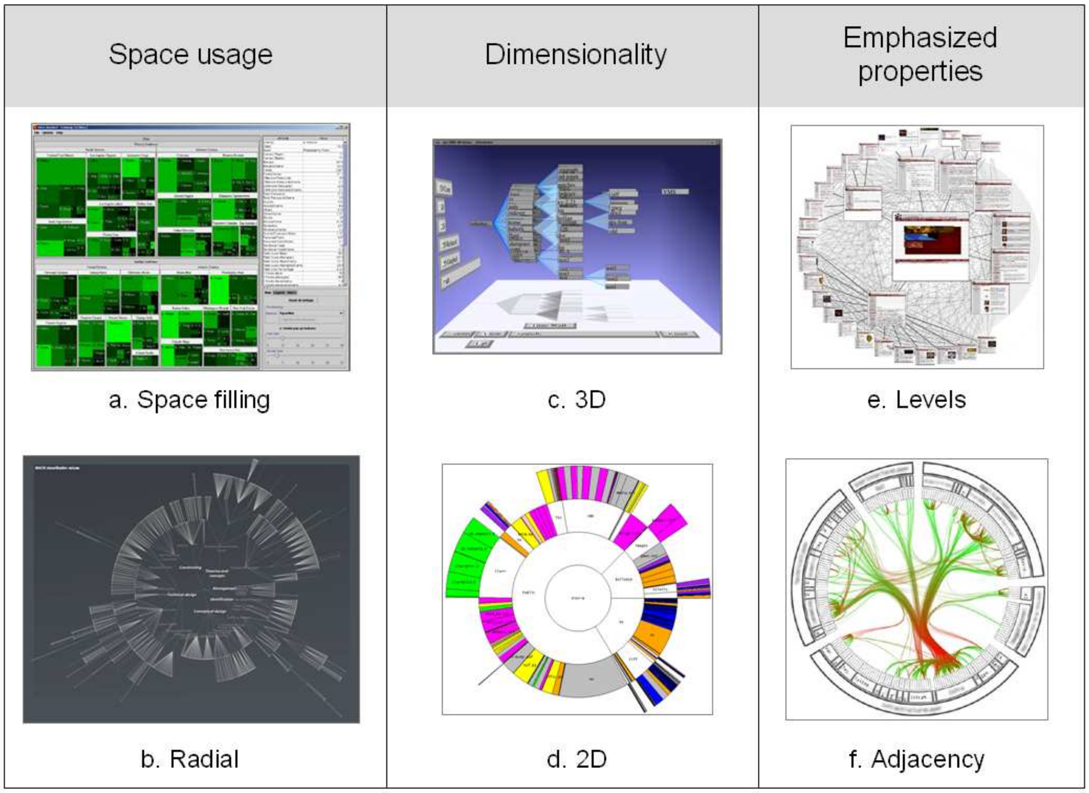


Figure 1.2: Visualizations of hierarchical data. Factors such as space usage, dimensionality and emphasized properties contribute to the diversity of the visualization's appearance even if the underlying data has a similar structure

Internet allows users to take more active roles. Online systems such as Stanford's Vispedia [13] allow casual users to select the visualization that they consider the best fit for representing tabular data. Google finance [30] provides its users with interactive and complex visualization of financial information. Large online communities are also popularizing the use of visualization to represent personal information such as its members' network of friends. However, we know very little about how people interpret the visualizations being used. Currently, there is no general curriculum teaching people how to interpret visualizations for more than simple graphs and plots, which are taught in grade school. Yet, anecdotal evidence from instructors and the results of research studies indicate that a significant subset of students struggle to comprehend the very images that are supposedly designed to make their understanding easier.

1.1 Motivation

Visualizations are becoming an integral part of everyday and work-related activities. Inaccurate visualization comprehension can lead to errors in safety for activities such as airport security, medical diagnosis and homeland security [45]. Research has shown that a significant number of individuals have difficulty in understanding visualizations ([21], [33]). Even seemingly simple visualizations are beyond the comprehension of a large and educated population [85]. With the advent of modern day science and the ability to generate complex visualizations representing relationships in science, this lack of ability to interpret visualizations becomes even more serious to the point where individuals may be prevented from entering key professions because of their difficulties in understanding the representations of the profession [53]. Understanding how to interpret simple graphs and tables is taught in secondary school, but after this, a student is on his or her own. Although students take numerous classes in reading literacy, none are taught in "visualization literacy."

This dissertation introduces the concept of *visualization literacy* which is defined as the set of skills and strategies required to successfully interpret modern scientific and information visualizations. This dissertation also supports the need to develop formal training for the development of visualization literacy in the general population. The development of a visualization literacy primer will be useful not only for visualization users, but also for designers. Ribarsky [69] argues that there is a dire need for research that will help users of visualization understand the concepts they are attempting to show, and a need for research that also will help creators of visualization to present the data being graphically summarized in ways that are more comprehensible to the viewers. Golledge [37] found that even simple spatial concepts may not be well understood by people including the visual representations used to "help" them understand complex problems. Moreover, he argues, without specific education, people may remain unaware of the spatial properties in an environment.

Visualization is a complex problem that integrates perceptual processes, cognitive processes and problem solving skills. Unfortunately, the current body of knowledge regarding comprehension of modern 2-Dimensional and 3-Dimensional visualizations is very limited. The approaches used to solve the problem of visualization comprehension can be classified into three groups: (1) creating explicit training for the existing visualization, (2) making an ad hoc change to the visualization, and (3) conducting user studies on variations of a visualization and selecting the best variation.

Training is usually done on the job and focuses on improving comprehension of a particular visualization applied to specific tasks. Although effective, training is time consuming and expensive, and companies usually select individuals with already highly developed visualization comprehension abilities excluding others from these work opportunities [6]. The biggest methodological problem of most training methods is that there is no objective measure of the difficulty of the problems used. Difficulty is usually based on the perceived difficulty by expert users of the visualization technique. Although there may be some correlation between this “judged” difficulty and the difficulty a novice user of the visualization experiences in understanding the visualization, the correlation is likely to be very small. This is because the novice viewer may be lacking implicit strategies for comprehending some or more key properties of the visualization that the expert takes for granted ([57]).

The second approach is ad-hoc improvement of a visualization. These kinds of custom modifications are designed to solve a specific problem. An example of such visualization modifications can be found in Worldlets [27]. This tool modifies 3D webs by using 3D thumbnails (similar to text- or image based thumbnails found in regular web pages). A limitation of this approach is that solutions are non-generalizable and their application to other visualizations and tasks do not guarantee that an improvement in visualization comprehension will be achieved. These changes to visualizations are usually implemented without evaluating their impact on the potential population of users, and they do not provide information regarding why does the improvement may or may not work.

In the last approach, the results from user studies inspire new visualization improvements. For instance, research by Weiskopf [89] designed visualizations based on the results from physiological research in motion and color. The major limitation of this kind of approach is that results from user studies do not always extrapolate to large and diverse populations, making this design process more like a hill-climbing technique which finds a local solution that may not uncover larger and more serious problems. Often user studies run on visualizations use computer graphics graduate students as subjects making the results applicable only to highly trained experts in the field. They are also usually specific to the domain and the type of visualization used.

In order to create training methods for the development of visualization literacy, *this dissertation presents a methodology for understanding how visualizations are comprehended*. The approach proposed here focuses on determining (1) what makes individuals better at comprehending visualizations, (2) what kind of errors can be expected from individuals in the general population, and (3) which properties make visualizations difficult to comprehend. The goal of this research is to create a systematic approach for the development of visualization literacy by answering these three main issues.

1.2 Research Statement

This dissertation evaluates a methodology for generating of knowledge regarding difficulty of visualization comprehension that can be used to create training programs that improve an individual's visualization comprehension. Figure 1.3 illustrates the methodology followed by this dissertation. This dissertation studied a visualization based on 2D orthogonal projections. The visualization was simplified so it can be analyzed by untrained viewers, and only one basic analytic task being asked from viewers (i.e., extract the orientation of the visualized object). The selection of a visualization based on projections and the extraction of a simplified and fundamental visualization task to be evaluated are part of the *Visualization Literacy Framework* phase. As shown in Figure 1.3, the methodology proceeds to gather the knowledge regarding visualization comprehension difficulty in three consecutive steps.

Step 1 focuses on identifying the cognitive factors that impact an individual's abilities to comprehend visualizations. This dissertation will thus focus on the effects of cognitive abilities on comprehending the visualization problems. *Step2* uses the cognitive factors having the largest effects to group experiment participants according to their cognitive skill level (i.e., low, medium and high). Then three questions are asked: Which visualization questions are difficult for participants with low skills but easy for participants with high skills? Which visualization questions are hard even for participants with high skills? And which visualization are easy for everyone? Thus, we can group the questions roughly into easy, medium and hard questions.

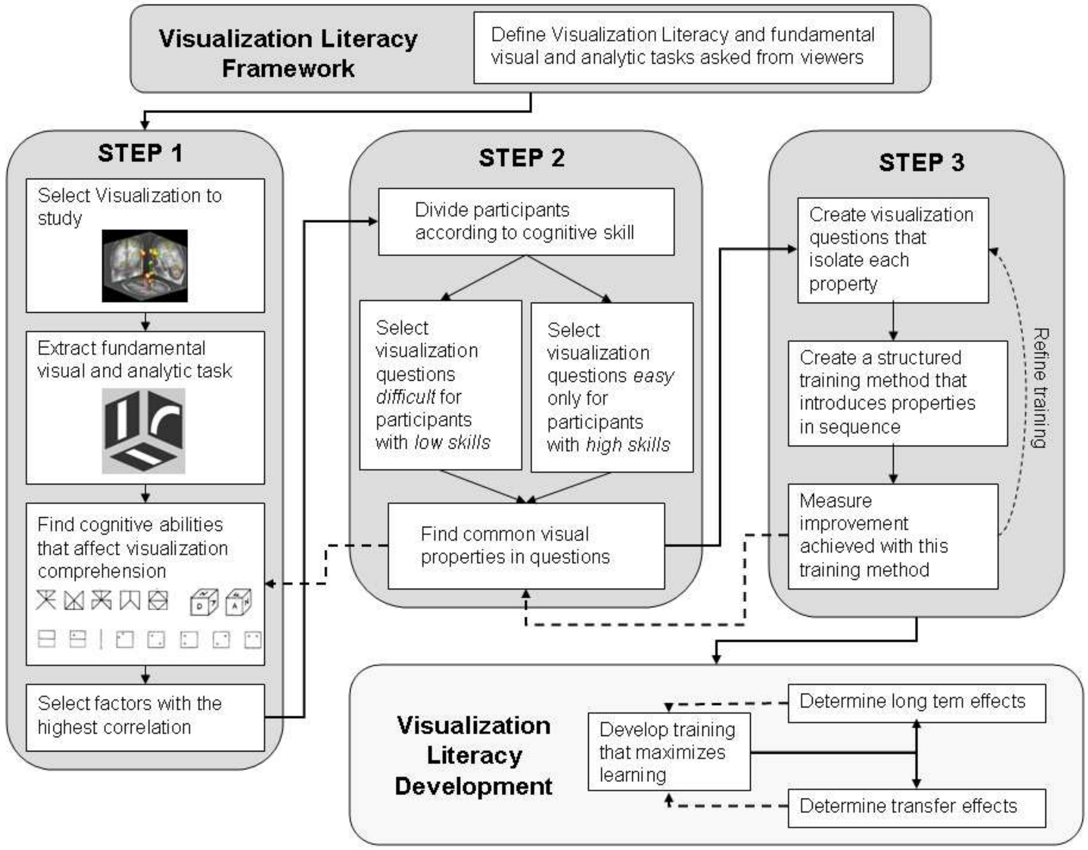


Figure 1.3: Research approach followed by this dissertation. Dotted lines indicate the next step after failure to find common question properties or failure to find improvement in the training

The common properties of those questions are then candidates for properties that make visualizations difficult to comprehend. If no common properties are found, other cognitive abilities can be evaluated. In *Step 3*, the properties uncovered are used to implement an incremental training method expected to develop the skills and strategies that constitute visualization literacy. The training method introduces the visual properties in order of difficulty based on the results found in Step 2. If the incremental training yields improvements that are better than random training, it confirms that the properties are directly correlated to the comprehension of this particular visualization. On the other hand, if the training does not yield the expected improvement in comprehension, other properties need to be evaluated in Step 2. Finally, the development of visualization literacy can be achieved by implementing training methods that maximize learning and transfer of skill. Techniques such as interactive visualizations, animations, alternative representations, text and video can be used.

1.3 Objectives

The overall objective of this work is to develop an approach that can be used to determine the factors that make a visualization difficult to comprehend by certain individuals and to use this knowledge in a structured training program that enhances visualization literacy. This dissertation explores the improvement of visualization understanding through the identification of properties of the visualization that cause comprehension problems in subsets of diverse populations. More specifically, this approach proposes a series of three steps. In each step, a general goal is given and specific objectives are specified as bullets.

First Step: (1) To understand what constitutes visualization literacy and select a class of visualization to explore, and (2) to determine what cognitive abilities are correlated with comprehension of the visualization family. This is done in order to determine the degree of difficulty for particular visualization problems. Specific tasks for this step are:

- To abstract a fundamental task that would be expected of users trying to study a visualization,
- To select problems and objects that present a variety of visual properties in the visualization (angle of rotation, object complexity, etc)
- To select a viable set of cognitive abilities and to find which of these cognitive abilities are correlated to visualization comprehension for the visualization task selected

Second Step: To identify visual properties that make the basic visualization difficult to comprehend. We use these properties to structure training starting with easy problems and bit by bit proceeding to more difficult ones in Step 3. The tasks involved in this step are:

- To have subjects do a comprehension test with various examples of the visualization family
- To cluster the visualizations by percent correct and cognitive ability scores in order to understand what is difficult for novice, intermediate and advanced viewers
- To look at the clustering of the visualizations and, through trial and error, attempt to determine which properties of the visualization make it difficult

Third Step: To compare the effect of incremental training to unstructured training. Incremental training consists of a set of visualization problems that introduce the visual properties found in Step 2 according to their level of difficulty. To complete this step the following task is necessary:

- To compare incremental training (easy to hard visualization comprehension) to unstructured training (no order)
- To determine if basic incremental training modifies the strategies used to analyze the visualization. This task is important to determine how much training will be needed for individuals to learn new generic visualization strategies and, through this, improve their visualization literacy.

The key aspects that make this approach unique is the focus on developing a theoretical basis as to what makes visualization tasks hard or easy to comprehend and the consideration of the large variability in skills that are found in the human population.

1.3.1 Contributions

This research has generated significant contributions in the field of scientific and information visualization. In particular, it contributes to the fundamental knowledge and research methods for the area known as "visualization for the masses". The following is a summary of the most significant contributions of this dissertation:

1. Introduced the concept of visualization literacy.
2. Demonstrated a viable method for the identification of visual properties that increase the difficulty of comprehending visualizations in populations with diverse cognitive skills.
3. Demonstrated that spatial ability measures are not only useful but necessary for studying visualization comprehension.
4. Demonstrated that individuals with low spatial abilities can be more readily trained in understanding more complex visualizations by compartmentalizing the training by order of difficulty.

1.3.2 Delimitation

To provide the reader with a clear scope of this research, those areas which are not part of this dissertation are as follow:

1. This dissertation does not attempt to develop a training methodology that maximizes learning and transfer of skill as described on the Visualization Literacy Development step shown on Figure 1.3. The training methodology and results presented in this dissertation are part of the validation of the visual properties that affect comprehension visualization.

2. This dissertation does not evaluate all possible tasks asked from visualization viewers. Instead, it focuses on a particular task in order to manage the large variability of comprehension levels expected in diverse populations.

1.3.3 Organization of the Dissertation

This dissertation is organized as follows: *Chapter 2* presents a precise definition of visualization literacy, work that has already been done in the area and a detailed discussion of the approach taken in this research. *Chapter 3* presents the background topics related to this reseat. It presents a detailed description of the nature of the problem addressed and the studies that have provided different solutions to making visualizations comprehensible. It also presents the theoretical bases for the approach taken with this research including the psychological background on cognitive abilities, with emphasis on spatial abilities and the educational literature on the impact of incremental training. *Chapter 4* describes the visualization test that is the focus of research in this work. This visualization test was designed to study the visualization problems introduced by the visual properties of the representation, when users need to create a mental representation of the object shown in the visualization in order to understand it. *Chapter 5* presents an overview of the three studies that provide the information necessary to complete Step 1, Step 2 and Step 3 of the methodology for the development of visualization literacy. *Chapter 6* contains a detailed description of Study 1. This study was run to determine the relationship between cognitive abilities and the comprehension of the visualization test described Chapter 5. The spatial ability tests, subject population used, experiment setup and analysis of correlation between cognitive abilities and comprehension are described in this chapter. The analysis follows in *Chapter 7*. In particular, the correlations between the spatial ability levels of the subjects and the accuracy of the subject's answers are used to determine how difficult a question of the visualization test was to comprehend. The difficult to hard problems are then analyzed to determine what is unique about their properties. *Chapter 8* describes Study 3 which compares incremental training to unstructured training. The incremental training takes the uncovered properties from Chapter 7 and uses them to design a set of visualizations that are grouped so that each property is introduced individually with multiple visualization problems. Users advance to the next property set which then only includes the learned property and the new property being introduced. In the unstructured training, the same problem sets are used but are randomly ordered. The results discussed in Chapter 8 show that the incremental trained subjects performed significantly better than the unstructured trained subjects. *Chapter 9* describes the expected contributions, the limitations of this work, and the future work that remains to be done on this topic to fully explore visualization literacy.

1.4 Chapter Summary

This chapter established the area of this research, introduced the concept of visualization literacy and established its importance in today's modern world. It then went on to overview attempts that have been made to train people in visualization literacy through visualization comprehension and noted that the focus has been on improving visualizations rather than improving human visual understanding. To fill this gap, research on how to train people in comprehending visualizations was described. Finally an overall plan for this document was given that led readers through the research to its successful conclusion, that is, a training method which appears to work. The next chapter will expand the motivation for this work by discussing visualization literacy in more detail.

Chapter 2
Visualization Literacy [1]

2.1 Introduction

Data visualization is an important skill in todays cyberinfrastructure environment, where everyone is expected to be able to understand information and data. However, the skills required to comprehend modern visualizations are not formally taught nor are there general training tools available. The pervasiveness of modern visualizations and large individual differences in the cognitive skills used to comprehend visualizations make it important to create training methods that order the visualizations according to their level of comprehension difficulty. This also allows the creation of training methods using item difficulty that is objectively measured and structured so that students solve problems starting from easy ones to progresively harder visualizations. of importance here is that the difficulty is not based on the techer's perception, but on objective measures.

This chapter addresses the need for improving visualization skills in the general population through the development of "visualization literacy" and presents a methodology to derive training methods for generic visualization skills.

2.2 Visualization Literacy vs. Visual Literacy

For many of today"s professions, especially those related to cyberinfrastructure, analyzing high dimensional data is a crucial skill. Most professions take advantage of computers which transform and display data so that a person can better view the relationships between the items of interest. This process is known as visualization. However, we know very little about how

[1] Parts of this chapter were published in the poster: Visualization Literacy: Maria C. Velez, Deborah Silver, Marilyn Tremaine, Karen Bemis. A Novice's Guide to Visualization. Extended Proceedings of Information Visualization 2008. Winner of the Best Poster Award.

people interpret the computer-based visualization techniques commonly used today.

The development of general knowledge, comprehension, creation and familiarity with the fundamental task or objective of a visual representation is known as *Visual Literacy*. Visualization literacy is a subset of this more general area. Although visual literacy is part of today"s general curriculum, teaching of “scientific and information visualization literacy” is limited to simple graphs and plots, which are taught in grade school. Anecdotal evidence from instructors and the results of research studies [48] [85] indicate that a significant subset of students struggle to comprehend the very images that are designed to make their understanding easier.

2.2.1 Visual Literacy

The term visual literacy, also known as visual knowledge and digital literacy generally refers to the knowledge, comprehension and familiarity with the fundamental task or objective of a visual representation. The term visual literacy was coined by Fransecky and Debes [32] and is defined as “a group of vision competencies which can be developed by seeing and at the same time having and integrating other sensory experiences. The development of these competencies is fundamental to normal human learning. When developed, they enable a visually literate person to discriminate and interpret the visual actions, objects and/or symbols, natural or man-made, that are [encountered] in [the] environment.” Since then, this definition has developed as the technological advances introduced by visual media and personal computers have made visual representations ubiquitous in society. Chauvin [14] defines visual literacy as “the ability to access, analyze, evaluate and communicate information in any variety of form that engages the cognitive processing of a visual image”. Both definitions underline the existence of an underlying visual knowledge or skill that is required to extract meaning from visual representations.

The effects of visual literacy, or the lack of it has been studied in multiple fields, and the research approaches are as different as the researchers’ goals and needs. For instance:

- In psychology and cognitive science, research focuses on understanding the perceptual and cognitive processes involved in the analysis of a visual scene. Results from research in this field include cognitive models and architectures that represent the structure of human visual perception and cognition [59].

- For communication professionals, visual literacy is a basic concept in the design and creation of visual messages for communication in different cultures and countries [93].
- Education fields concentrate their efforts in the development of instructional approaches to visual literacy. Such efforts result in the development of new curriculums, visual problem solving strategies and evaluation methods [77], [71].
- In computer interface design, the emphasis is placed on the creation of a visual vocabulary, that is, the creation of interfaces and visualizations that use visual representations already familiar to scientists. Results from this field include the development of visualizations and the improvement of existing ones that better meet the knowledge and expectations of scientists from different fields [71] [61].
- Strikingly, the individuals using a large number of visual displays, e.g., finance, economics, architecture, all physical sciences, medicine and engineering, do not explore the concept of visual literacy despite the fact that it is necessary in these fields.
- The need to develop visual literacy in order to comprehend scientific visualizations has been recognized in fields such as geology and geographical sciences. Golledge [37] supports the need for training and argues that everyday experiences alone is not enoygh to develop complete spatial knowledge and analytic strategies, and that formal training is needed if individuals are to pursue academic areas such as geology. Ribarsky [69], a visualization researcher, argues for research that will help users of visualization understand the concepts they are attempting to show and also help creators of visualization to present the data being graphically summarized in ways that are more comprehensible to the final viewer.

- In the scientific and information visualization communities, visual literacy has been defined by means of taxonomies and classification of visualizations. Some of these taxonomies use user task as a classification parameter. Lohse et al. [58] created a categorization of basic visual representations using graphic designers to determine which visualization would be better for particular tasks. Tory and Moller [81] classified visualization tasks according to how much spatial layout affects the analysis of the visualization. Amar et al. [3] defined ten basic analytic activities of users in affinity diagrams.

2.2.2 Visualization Literacy

This dissertation defines *Visualization Literacy* as the *set of skills and strategies required to successfully interpret modern scientific and information visualizations*. It also presents a different approach to the development of the skills needed by viewers of scientific and information visualizations based on the concept of visualization literacy.

Ribarsky [69] argues that there is a dire need for research that will help users of visualization understand the concepts they are attempting to show, and that also will help creators of visualization to present the data being graphically summarized in ways that are more comprehensible to the viewers. The need for the development of visualization literacy is based on the belief that formal training is required for the development of visualization literacy in the general population. Golledge [37] found that even simple spatial concepts may not be well understood by people, including the visual representations used to "help" them understand complex problems. Moreover, he argues, without specific education, people may remain unaware of the spatial properties in an environment

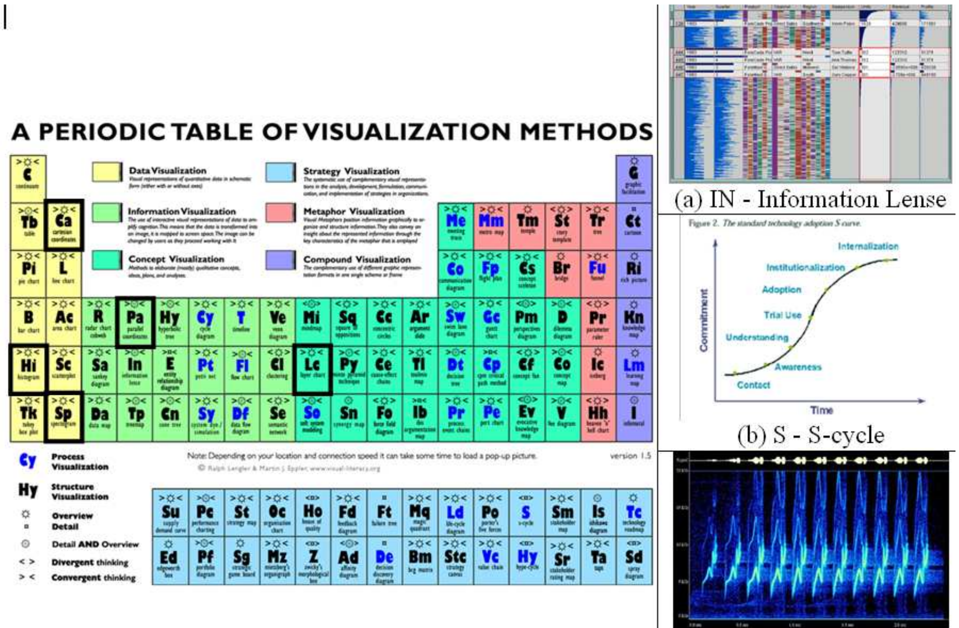
2.3 Development of Visualization Literacy

The development of a visualization literacy primer will be useful not only for visualization users, but also for designers. The knowledge that constitutes visual literacy is gradually acquired and refined through everyday experiences and formal education. Evidence indicates that the spatial concepts and skills that are automatically developed without input from educators are mostly lower level analytic skills with incomplete or incorrect spatial concepts. As mentioned before, studies by Golledge [37] lead to the conclusion that even simple spatial concepts may not be well understood by people without specific education.

The education community has recognized the need to increase the emphasis placed on visual literacy in the current curriculum. Traditional arts programs include concepts such as areas of drawing and painting; environment design like architecture, landscape and interior design; information design such as publications, web sites, film and photography, and visual communication which includes maps, charts, graphs and diagrams. However, scholars agree that visual literacy should be regarded as important as mathematics, science and literature. To facilitate the student exploration of visualization methods in different domains, the Visual-Literacy.org project created a periodic table of visualization methods [68] shown in Figure 2.1. In the periodic table, visualizations are categorized across five dimensions that describe the nature of the visualizations: Complexity of visualization, content area, point of view, type of thinking aid and type of representation. This classification includes some scientific visualizations which are highlighted in Figure 2.1. The VisTe (Visualization in Technology Education) project [92] designed a curriculum to promote the development of knowledge in technology, mathematics and science where visualization literacy is regarded as a fundamental skill. Aaron and Wieble [18] propose to improve the current high school curriculum to go beyond basic drafting skills to include a visual science course.

As visual representations grow in complexity and become ubiquitous, educators have come to recognize the need to improve visualization literacy in the general population. However, unlike reading skills (literacy), the way visualizations are understood and techniques to teach the skills necessary for their comprehension has not been deeply explored. Some work exists on how individuals understand simple graphs [2] [19] [5] and very few studies have focused on comprehension of scientific visualizations [48] [85] [72].

This dissertation proposes a methodology to derive the information required to create programs aimed to develop generic visualization skills. This process starts by (1) identifying the fundamental visual and analytic tasks that visualization developers are asking from viewers and (2) determining the nature of the errors made by users and finding the properties that increase comprehension difficulty and the strategies used by experts. Then, (3) these properties



(a) IN - Information Lense
(b) S - S-cycle
(c) Spectrogram

Figure 2.1: A periodic table of visualization methods from [68]. The three images to the right of the periodic table present examples of the visualizations included in this classification. Visualizations used in scientific visualization are highlighted. (a) Information lenses visualization belongs to the category of information visualization, (b) S-cycle is in the category of strategy visualization and (c) Spectrogram visualization appears in the category of Data visualization and it is one of the scientific visualizations in the table.

are used to quantify visualization difficulty and outline the comprehension limitations that can be expected in diverse populations.

The knowledge generated by this approach can be applied to the creation of training methods that develop the "competences" for the required level of visualization literacy. In the best possible scenario, generic training can lead to transfer of skills to similar and more complex visualizations. The knowledge resulting from this approach can also allow the ranking of visualizations from easy to hard. While what is a difficult visualization may seem obvious, it is not. In [85], what the visualization experts had deemed difficult turned out not to be accurate. Therefore, studying the errors and model strategies is necessary to identify difficulties.

2.4 Chapter Summary

This chapter focused on prior research carried out on visual literacy, in particular, how specific fields have defined it. Its purpose was to lay the motivation for this research which has developed a method for determining what difficulties users have in comprehending a visualization. The next chapter presents a comprehensive literature review that describes what has already been done in the area of helping users to understand visualizations and also the psychological basis for the approach followed in this dissertation.

Chapter 3
Background

3.1 Introduction

Researchers are constantly looking for new and better ways to visualize complex data. As the research discussed in this chapter shows, creating usable visualizations for complex data presentation is a non-trivial process, in large, because of difficulties that appear when visualizations are designed to be used by non-experts and the general public. These problems can be characterized in three aphorisms: *to display is not to explain; seeing is not perceiving; perceiving is not understanding*.

To display is not to explain: A good design does not guarantee that the visualization will be self explanatory and intuitive for all individuals. Visualization designers use their expertise to show the data properties in the best possible way, considering factors such as data scale and complexity, use of space, preferred dimensionality, and emphasis of data properties. It is often the case that untrained visualization viewers will not understand the information shown by the visualization unless the mapping between data and visual representation is explained through training.

Seeing is not perceiving: The study of human factors in visualization usually focused on the effect of perception in the comprehension of visualizations. Theories of perception have been successfully used to improve visualizations and these new developments in visualization are often evaluated with user studies. Examples of visualization improvements based on theories of perception are stereo viewing, color and contrast, shading, shadows, shape from texture and shape from motion. Visualization comprehension involves not only perceptual processes but also cognitive processes and problem solving skills. Therefore, visualizations designs based on theories of human perception still do not take into account complex cognitive processes that are part of the visualization comprehension.

Perceiving is not understanding: Cognitive processes such as spatial abilities, working memory and other higher thinking processes receive information gathered by the perceptual system and, in essence, these cognitive processes constitute what is considered as thinking. Studies have found that there are large individual differences in cognitive abilities in the general population. These differences are due to genetic, cultural and practice variability and have been found to affect visualization comprehension. This dissertation uses comprehension difficulties that emerge at the cognitive level to explore how properties of a visualizations that affect comprehension. That is, this dissertation explores the limits in visualization comprehension imposed by the individual's cognitive abilities.

This chapter begins with a description of the most relevant problems in visualization comprehension found in the literature. Comprehension difficulties are classified into problems related to (1) the visual display, (2) the task asked for from users and (3) individual differences found in large populations. The section on visualization difficulties due to individual differences is followed by an in-depth presentation of spatial abilities and other cognitive factors that are relevant to the general comprehension of visualizations. These cognitive factors are used in this dissertation as mediating variables in the discovery of the properties that make a visualization difficult to comprehend for populations with diverse cognitive skills.

After discussing the problems in visualization comprehension, this chapter continues with a presentation of the various approaches used to solve the problem of visualization to overcome these comprehension issues. Solution approaches are classified as: (1) creating training for an existing visualization, (2) making ad-hoc changes to improve the visualization, and (3) conducting user studies to guide changes that improve the visualization.

3.2 Visualization Comprehension Problems

Computer based visualizations are an integral part of the tools for exploration and analysis of data, and they have contributed dramatically to the performance and accuracy in such tasks. However, a wide range of studies in different fields show that there are comprehension problems that need to be addressed. Cognitive abilities are currently an active area of research [55], but the results from these studies cannot be immediately related to computer-based visualization problems. The focus of most research on computer-based visualization comprehension is on finding which cognitive factors affect the comprehension of a particular visualization. Studies have pointed out three general sources of comprehension difficulties: (1) users' individual differences, (2) the nature of the visual representation and (3) the visual task asked of the users. As will be shown in the remainder of this section, these sources of comprehension difficulty interact making it difficult to identify the impact that each factor has in a particular visualization.

3.2.1 Visual Representation

Visualization designers commonly manipulate visual characteristics of a visualization technique like dimensionality (2D or 3D) color, rendering, etc., in order to maximize the amount of data that can be displayed at a time. For example, Cockburn and McKenzy [20] asked subjects to find a web page among paper printouts of web pages taped to a clothesline (3D view of a 3D environment). They found that subjects found web pages much more quickly in the clothesline condition and concluded that the 3D view was better because subjects were able to use spatial memory in their task. However, no standardized spatial ability tests were administered to control for this factor. It is hard to accept the proposition that spatial memory was the cause since the real world environment had many more cues in it than a 3D environment any of the which could have given subjects an advantage. Allen [2] examined the cognitive load imposed by different 2D visualizations. Names were organized either by semantic similarity or simply organized in an alphabetical matrix. Subjects found names in the complex semantically similar search space more quickly than in the matrix organization. High spatial ability subjects performed less quickly in the semantic arrangement than in the matrix arrangement. This paper illustrates again that spatial ability is an important variable to use in studies comparing data representations, and that it is a predictor of performance. A study by Cockburn and McKenzie [19] looked for differences between 2D and 3D interfaces in a task that involved storing and retrieving web page thumbnail images. No significant difference in efficiency was found between both interfaces, while users expressed a strong preference toward the 3D interface. Although many people preferred the 3D interface, it might have been because of the novelty of the display. The 3D interface appeared to add no advantage to the search. Ark et al. [5] found that in an object recognition task, it is not only dimensionality (2D iconic vs. 3D realistic) but layout (realistic vs. abstract) that impacts users' comprehension. They did not relate their results to the spatial ability of their subjects, but given the preponderance of male subjects who used computers on a daily basis, it is likely that all had high spatial abilities. Results might have been less clear if a more diverse population had been studied.

Research results do not always support the common notion that 3D visualizations are better data representations. There is usually a trade off between the freedom for spatial exploration and complexity. Uran and Janssen [83] found that problems in the use of Spatial Decision Support Systems (SDSS) are usually generated by a lack of support for the evaluation of the spatial relations displayed in 3D systems. Westerman and Cribbin [91] represented "semantic distances" between documents in a 2D plane. They then added "newness" of documents as a third dimension. They found that document search time increased precipitously in the 3D task and was highly correlated with subjects' spatial ability (measured with the Paper Folding Test [26]). Thus, the cognitive load added by the 3D navigation outweighed the perceived advantage of presenting two related variables simultaneously. Similarly, Modkeska and Chignell [62] found no benefits from using a 3D compared with a 2.5D (series of 2D birds-eye "snapshots") virtual environment. In fact, low spatial skills negatively impacted users' performance in the 3D representation. Swan and Allan [78] also found no significant improvements using a 3D visualization instead of a text-based representation in a bibliographical search task. Spatial abilities were found to be the most significant factors in the effectiveness of the 3D visualization. Chen and Yu [17] conducted a meta-analysis of a set of search and retrieval studies that used a visual spatial component and measured accuracy and performance time. They concluded that all users, no matter what their spatial ability level, would perform better in simple rather than complex visual spatial interfaces. In a study by Cribbin and Chen [21] it was found that the use of a visual (vs. textual) information retrieval interface may increase the comprehension problems. Orientation in the 3D environment introduced navigation problems that blocked the solution of the actual search task. Likewise, Westerman and Cribbin [91] concluded that for the task of information search, the overload of having a 3D spatial layout outweighs the benefit of having more data represented in the visualization.

Thus, although the use of additional characteristics of visualizations for representing information relationships (e.g., dimensionality), in theory, looks to be a useful approach, studies are indicating that individuals (especially those with low spatial skills) are significantly disadvantaged by these innovations. This leads to a quandary. The world needs to represent its complexity in order to manage it, yet people may not have the ability to understand the representation.

3.2.2 The Visualization Task

The third and final source of comprehension difficulty is the visualization task itself. There are visualization tasks that are cognitively difficult no matter how they are represented. Rizzo et al. [70] showed that individuals that have difficulty with the Shepherd and Metzler mental rotation test [74] can improve their mental rotation ability through training in a VR environment, although they failed to find improvement in other 2D paper-based tests of mental rotation. Thus, the visualization on paper required an additional level of processing that the VR task did not, making it a much more difficult visualization. Mental rotation without visual support has been found to be difficult. DeJong et al. [25] found that in teleoperations, users must mentally move video cameras to obtain the necessary video images during an operation. They found that if those mental transformations (rotation, translation, etc.) are not represented in the computer interface, viewers' performance is negatively affected.

Navigation is also a visualization task that has proven to be difficult. Sjolinder [75] points out that there are large individual differences affecting wayfinding in hypermedia navigation. Although gender differences have a strong effect in navigation, a number of studies emphasize the fact that it is not just females that have difficulty navigating in real [50] and virtual environments [17]. Kato and Takeuchi [50] found that females with high spatial ability had different navigation strategies than those with low spatial ability, and Galea and Kimura [33] found that females with high spatial ability navigate equally well using cardinal cues or landmarks. Text based tasks also affect visualization comprehension. Reading foreign language text with multimedia aids [46], in particular with visual annotations, has been found to be difficult for users. The cognitive load of processing the visual cues negatively affected the learning. Ability to search an email archive using 2D grids in a task-based user interface [40] has also been found to lead to inaccuracy problems.

3.2.3 Individual Differences

Spatial abilities are the most common cognitive skills correlated with comprehension difficulties. A study by Swan and Allan [78] investigated the usefulness of a 2D visualization called "Aspect Windows" and a 3D visualization of document inter-relationships, e.g., content similarity represented by closeness. This study found that when subjects searched for documents in the 2D and 3D representations, those with higher spatial ability scores (measured with the Paper Folding Test) searched faster in the Aspect Windows system than those with lower scores. The search results in the 3D version of the application were confounded by difficulties with the 3D input device, which rendered them unable to study the interaction between visual representations and level of spatial skill. Bryce Allen [2] studied the effectiveness of information retrieval in standard bibliographic information systems. The information retrieval process requires users to memorize, comprehend and establish connections between different concepts or index keys in the search system. The research results indicated that the success of online searches in such systems correlates with different cognitive abilities, such as the ability to reason from first premises to a conclusion, the ability to understand the language of the search and the ability to explore spatial layouts visually (spatial scanning ability was measured with the Maze Tracing Speed Test and the Map Planning test, and perceptual speed was tested with the Number Comparison test and the Identical Picture Test). A previous study [1] had already identified the effect of several cognitive factors in search performance using a standard computerized CD-ROM index. Spatial abilities have also been found to affect the strategies used to analyze visual environments. Chen and Czerwinski [16] found that navigation and search strategies in a 3D environment changed according to users' spatial skill level and previous experience (e.g., computer expertise and current computer usage). Not much research has been conducted in the interaction between spatial abilities and strategies of analysis in other visualization techniques.

Differences in visualization comprehension have also been reported between genders. Part of such differences can be attributed to gender differences in spatial ability. Hubona and Shirah [44] asked male and female subjects to perform three spatial tasks: object matching, alignment and resizing. Males performed better on the object matching and resizing tasks, while females outperformed males in the alignment of objects in 3D space. In a study by Cutmore et al. [22], both males and females were found to use landmarks to effectively navigate from the center to the outside of a maze in a virtual environment. However, it took more trials for females to achieve the same level of performance. They also found that users with superior visual-spatial ability (measured with a block design test from the WAIS-R test battery [88]) were significantly more accurate in distance estimation.

Gender was also found to be a good predictor of navigation performance with males outperforming females. Czerwinski et al. ([23], [79]) studied the gender differences in 3D virtual environment navigation. They found that larger displays and a wider field of view improved female performance in the navigation tasks so that it equaled male performance. In this study, the Shape Memory Test was used to measure spatial ability. Low scorers on this test (females) performed equal to high scorers with the wider field of view. However, it was not understood what caused this improvement.

Finally, users' previous experiences influence different aspects visualization comprehension. Eye gaze movements in 3D virtual surgery training application have been found to be different for novices and experts [57]. These differences imply that novices may be missing visual clues fundamental to visualization comprehension causing them to make more errors than experts. Golledge [38] argues that people develop "common sense" spatial knowledge that is incomplete and full of inaccurate concepts that affect comprehension of visualization. Gordin and Pea [39] identified students' difficulty to comprehend the visual representation of the data as a potential problem in the integration of scientific visualization into high-school education. Students are not familiar with the metaphors and spatial layouts that are intuitive for scientists. However, scientists have likely entered their chosen field, in part, because they possessed higher spatial skills. Thus, acquisition of the metaphors and spatial layouts was easier and more intuitive for them to acquire than is likely with a general high school population.

Since users' spatial abilities have been found to be correlated with accurate comprehension of visualizations, they will be used as a fundamental component of the research described in this document. Unlike the prior studies carried out on visualization comprehension, the diversity of spatial ability and the multiple abilities that compose it, suggest that any tests on visualization comprehension need to include these two factors as variables.

Overall, visualizations can be hard even for highly skilled individuals because of the complexity of today's information. Users of visualizations need to be brought up to a higher skill level through either appropriate cues in the visualization or appropriate training.

3.3 Factors of Spatial Ability

There are many definitions of spatial ability, but it is generally accepted to be related to skills involving the retrieval, retention and transformation of visual information in a spatial context [41]. Researchers have broken apart the concept of spatial ability into specific factors that are believed to contribute to spatial comprehension. Unfortunately, factor labeling and definitions vary from one researcher to another. Kimura [52] defines six spatial factors that have a broad acceptance because they can be distinctly identified by experimental measurement. They are: Spatial Orientation, Spatial Location Memory, Targeting, Spatial Visualization, Disembedding and Spatial Perception. This is the classification of spatial abilities that will be followed in this dissertation.

1. *Spatial Orientation* is the ability to accurately estimate changes in the orientation of an object. This skill is evaluated with tests that present 2D objects (e.g., letters, figures in the center of a clock face, and simple shapes) and 3D objects (e.g., Cubes, sets of cubes, and photos of real objects) rotated in 2D or 3D space.

2. *Spatial Location Memory* is the ability to recall the position of objects in an array. The commercial game, Memory Game, is a good test for spatial memory. Tests of spatial location memory present an array of realistic or geometric objects that should be memorized. Then, participants are presented with a second array or with portions of an array where discrepancies with the original array must be identified.

3. *Targeting* refers to the ability to intercept projectiles or throw them at a target. It is difficult to categorize this ability, since it is highly related to motor ability [52]. Targeting is often measured with tests that require throwing a physical object to a target.

4. *Spatial Visualization* is the ability to recognize and quantify the orientation changes in a

scene. Although this ability looks very similar to mental rotation, this skill does not require mental rotation of objects, but the estimation of one's position in relation to a static object. Spatial visualization is also defined as the ability to imagine a result after folding or assembling parts of an object. The most characteristic tests of spatial visualization require a participants to imagine what the final result is after a piece of paper is folded.

5. *Disembedding* is the skill that allows a person to find a simple object when it is embedded in a more complex figure. This factor is also referred to as Flexibility of Closure or Field Independence [52]. Tests of this factor require participants to find a model that is embedded in a distracting pattern.

6. *Spatial Perception* refers to a person's ability to determine what the prevailing horizontal and vertical directions are in a scene where distracting patterns are present. One test of this ability requires participants to draw the water level line inside a transparent jar that has been tilted. Other tests require subjects to align (horizontally or vertically) a pattern that is surrounded by a frame.

These spatial factors have been measured on large populations and shown to reveal large differences in performance. Of particular interest are the gender differences in these skills. Males score consistently higher than females in spatial orientation and targeting. However, females score consistently better than males in disembedding and spatial memory tasks. Spatial perception and spatial visualization offer a slight advantage for males. These skills have been shown to be important for comprehending visualizations ([78], [16], [22], [44]).

As visualizations become more common, it is evident that we need to address the problem of barriers to information access and comprehension by a significant subset of the population. Psychological research suggests that the development of spatial abilities can be attributed not only to biological but also to sociocultural factors [60] making spatial ability improvement possible through appropriate training. Improvement in specific spatial test scores after training does not always transfer to other spatial tasks. This has been attributed to the nature of the tests which are often too specific to build a general skill and rarely consisting of enough mass practice and knowledge acquisition to create a higher level skill transfer [87]. This research will not focus on improving scores in the general spatial ability tests but on using the variability of

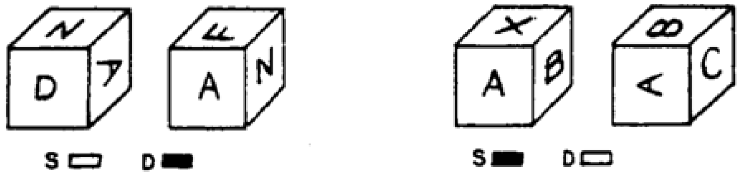


Figure 3.1: Examples of questions from the Cube Comparison Test (S-2).

subject performance in these tests to create a higher resolution in measuring problem difficulty with the visualization family being studied.

Three of the above spatial factors: Spatial Orientation, Spatial Visualization, and Disembedding will be measured in this research. They were selected as most relevant to the visualization family being studied. They will be measured through the Kit of Factor Reference Cognitive Tests [26] available at Educational Testing Services, Inc. (ETS) in Princeton, New Jersey and the Shephard and Metzler Mental Rotation test [74]. All the tests are paper-based; they are time-limited and consist of two parts of equal length. Several factors guided our selection of these tests since there are many to choose from. They are (a) easy to administer, (b) easy to score, (c) well-studied on large populations, (d) readily available and (e) shown to measure the 3 spatial factors perceived to be relevant in the visualization task. Note: not all of the tests selected are likely to be highly correlated with the visualization task. Thus, multiple tests were chosen to cover this space. The following are the spatial ability tests used in this dissertation.

Cube Comparison Test (S-2): This test measures Spatial Orientation. As illustrated in Figure 3.1, two cubes are shown and participants are asked to determine if both cubes can be the same cube in different rotations. The test consists of two 3-minutes sections with 21 questions each.

Vandenberg Mental Rotation Test (M.R.T. Test): This is one of the most commonly used tests of spatial orientation and it is based on the Shepard and Metzler Mental Rotation Test [74]. As shown in Figure 3.2, participants are asked to identify which of the comparison figures on the left are identical to the original figure on the right. Participants are given six minutes to solve two sets of 20 questions.

Paper Folding Test (VZ-2): This is a test of Spatial Visualization. Each test item presents a series of two or three folds to a paper sheet. After the piece is folded, a hole is punched in

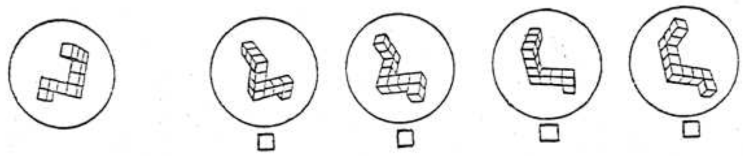


Figure 3.2: Question from the Vandenberg Mental Rotation Test (M.R.T. Test).

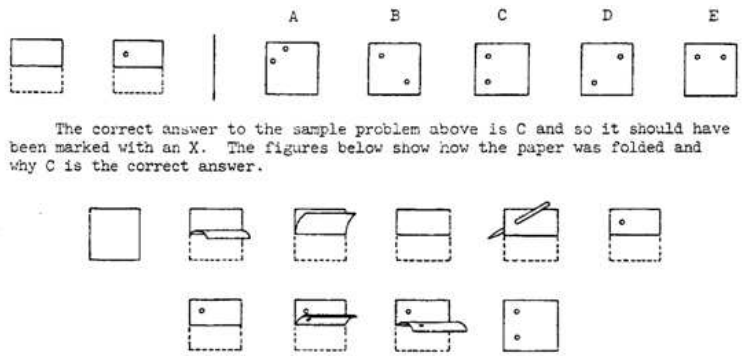


Figure 3.3: Question from the Paper Folding Test (VZ-2).

the paper. The task consists of identifying, from five drawings, the one that corresponds to the unfolded sheet. Participants are given three minutes to solve 10 problems in this test.

Hidden Patterns Test (CF-2): This is a test of the Disembedding spatial skill. Each question asks the participant to determine if a given shape is embedded in a geometric pattern as shown in Figure 3.4. Each test section has 200 patterns and a test taker is given 3 minutes for the task.

Two other cognitive factors will be evaluated: Visual Memory and Perceptual Speed. Even though they are not directly related to spatial ability, they have been found to be related to the

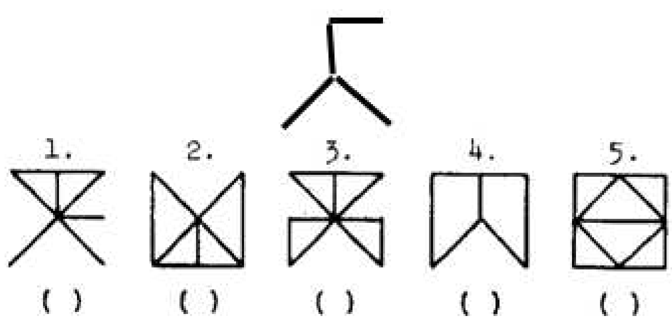


Figure 3.4: Question from the Hidden Patters Test (CF-2).

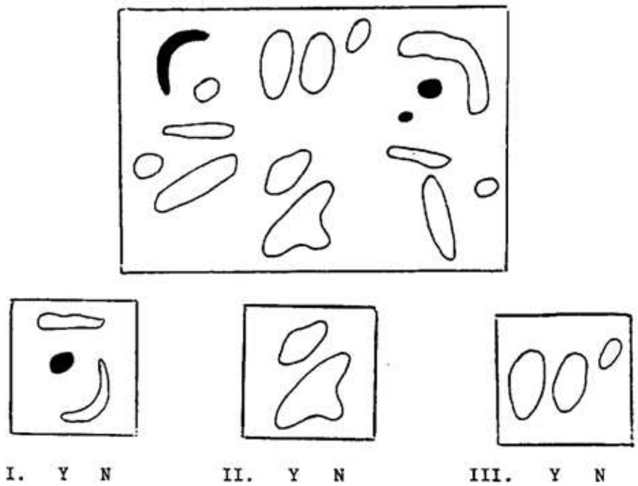


Figure 3.5: Question from the Shape Memory Test (MV-1)

task of visualization comprehension.

Visual Memory refers to the ability to remember the configuration, location and orientation of irregular shapes or objects. Studies have found that many visualization techniques require users to form a mental image of an object, and remember it for a short time, the results from this test can be used as an effective way to control for differences in memorization ability. The Shape Memory Test (MV-1) will be the test used to evaluate visual memory. In this test, participants are asked to identify groups of irregular shapes that were seen in an array on the previous test page as shown in Figure 3.5. Each part gives the participants four minutes to memorize the array, and four minutes for identifying which of the 16 items were present.

Perceptual Speed is the cognitive ability to rapidly find a target symbol in a set of symbols or patterns. This factor will be used as a control factor since it is likely to affect the time a subject takes to analyze the visualization questions. This cognitive skill will be Identical Figures Test (P-3). This is a test of Perceptual Speed. Participants are asked to recognize a figure appearing on the left from a set of five similar objects on the right. Subjects are given one and a half minutes in each part of the test to identify 48 figures.

This dissertation focuses on skills found in diverse populations, therefore it is necessary to determine what range of scores in the psychometric tests can be expected. Table 3.1 presents the test scores reported by the Kit of Factor Reference Cognitive Tests [26] and other studies

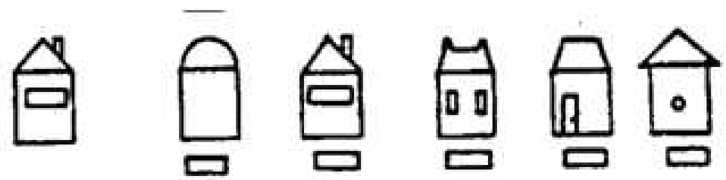


Figure 3.6: Question from the Identical Figures Test (P-3)

Table 3.1: Statistics on the psychometric tests used in this dissertation

Test	Statistics Reported by ETS [26] and other studies		
	Mean	S.D.	Sample
Vandenberg Mental Rotation Test (M.R.T.)	14.5 8.96	5.9 4.44	501 males undergraduate students [66][2] 1264 females undergraduate students [66][2]
Cube Comparison Test (S-2)	5.2	5.1	574 male Naval recruits (Part 1 only)[1]
Paper Folding Test (VZ-2)	11.5 10.4	3.7 3.7	300 males (11th, 12th grade)[1] 329 females (11th, 12th grade)[1]
Hidden Patterns Test (CF-2)	147.9 141.6 139.9	38.3 33.2 40.4	300 males (11th, 12th grade)[1] 329 females (11th, 12th grade)[1] 189 High school. males[1]
Shape Memory Test (MV-1)	21.4	4.3	574 male Naval recruits[1]
Identical Figures Test (P-3)	53.2 56.7 49.6	11.2 10.2 9.8	males (11th, 12th grade)[1] 329 females (11th, 12th grade)[1] 294 6th graders[1]

[1] Study results published by the Kit of Factor Reference Cognitive Tests [26].
[2] Scores computed with correction for guessing: C-I/n-1; C=correct answers, I=incorrect answers, n=number of possible options in each test item

with large samples.

Five scores were calclated for all spatial ability tests:

- Percentage of correct answers in all test questions (PCT)
- Percentage of correct answers in all answered questions (PCA)
- Percentage of incorrect answers in all test questions (PIT)
- Percentage of incorrect answers in all answered questions (PIA)
- Guess-adjusted (GA). The formula used is C-I/n-1; C=correct answers, I=incorrect answers, n=number of possible options in each test item

Table 3.2: Summary of spatial factors studied in this dissertation and the psychometric tests used to evaluate them

Spatial Factor	Definition	Test
Spatial Orientation	Ability to accurately estimate changes in the orientation of an object	Cube Comparison Test(S-2) Mental Rotation Test(M.R.T)
Spatial Visualization	Ability to recognize and quantify the orientation changes in a scene by identifying ones position	Paper Folding Test (VZ-2)
Spatial Location Memory	The ability to remember the configuration, location and orientation of figural material	Shape Memory Test (MV-1)
Disembedding	Ability to find a simple object when it is embedded in a more complex figure	Hidden Patterns Test (CF-2)
Perceptual Speed	Speed in comparing figures or symbols, or carrying out other very simple tasks involving visual perception	Identical Figures Test (P-3)

Given that all the tests of cognitive abilities are time constrained, the scoring methods are affected differently by the participant's speed. For instance, the percentage of correct and incorrect answers in all the test questions is affected by the number of questions left unanswered, therefore conveying not only the participant's accuracy but also his or her speed. The percentage of correct and incorrect answers in all answered questions reflects only participant's accuracy. The guess adjusted score is a traditional formula for computing the score that accounts for a participant's guessing by subtracting a fraction of the incorrect answers from the count of correct answers.

The scores of the spatial ability tests are used in all steps of the approach proposed by this dissertation. In the first step a correlation analysis looks for significant correlations between the scores obtained in five of the tests and participant's performance in the visualization test (time and accuracy of answers). The second and third steps use the test scores to classify experiment participants as low, medium or highly spatial skilled. Table 3.2 presents a summary of the factors of spatial ability and the tests used in this dissertation.

3.4 Solution Approaches

The approach taken to solve the problem of visualization comprehension is based on modifying visualizations. In an attempt to define a taxonomy of solutions, we classified them into three groups based on their general approach: (1) creating explicit training for the existing visualization, (2) making an ad hoc change to the visualization, and (3) conducting user studies on variations of a visualization and selecting the best variation. The following three sections will present the general advantages and limitations of each approach, as well as results obtained by representative studies in the field of data visualization.

3.4.1 Training Techniques

Training is a common technique used to overcome the comprehension problems faced by novice visualization users. Attempts have been made to develop training methods that improve general abilities related to visualization comprehension such as the work done by Rizzo et al. [70] but most training methods focus on the development of comprehension skills for a particular visualizations.

Training has successfully developed particular visualization comprehension skills. Kasten and Ishikawa [49] developed training methods to improve the skills of geoscience students based on the recognition of the parallels between spatial and geoscience tasks. Piburnn et al. [67] developed two training modules for 3D topography and 3D geologic blocks. This training method uses knowledge of geology and geology-inspired examples to explain visualizations. Mechanical and civil engineering researchers have developed training techniques to facilitate the understanding of concepts such as orthogonal projections, slices and cutting planes. Osborn and Agogino [65] created an interface that used the metaphor of a “pool of water” to illustrate the effect of a cutting plane in 3D objects. This training application is based on the direct manipulation of a 3D object and the observation of changes in the orthographic views and cutting planes. Virtual reality has been successfully applied in training applications for medicine and surgery [63], [42]) and car driving [7]. Video games have been known to produce mixed outcomes in terms of improving spatial ability. Intensive training in Tetris [87] was found to improve spatial strategies that were highly related to the kind of spatial transformations used in the game (90 degrees rotations) and the Tetris objects. As a result, the improvement obtained in the ability to play the game did not transfer to other objects and other spatial skills.

The effectiveness of training as a method to improve performance depends on factors such as the design of the computer interface [24] and the age [34] and cognitive skills [11] of the trainees - both identified as sources of learning difficulty for trainees in computer software training. Therefore, effective training must consider the training needs of large and diverse populations in order to achieve improvement for all levels of skill.

The largest limitation of the training for visualization comprehension is the limited research in determining the difficulty of the problems used in training. Difficulty is usually determined by the designer of the training technique or an expert in the visualization, but as shown by research, novices and experts have large differences in their approach to solving the problems and comprehending the visual properties used ([73] [57]) leading to differences in the degree of difficulty of the visualization problems.

3.4.2 Ad-hoc Visualization Improvement

This is arguably the predominant approach taken by the academic community in the field of scientific visualization. Ad-hoc modifications are usually motivated by the complexity of the data, the needs of potential users and specific limitation in existing visualizations. Smeulders and Heijs [76] developed several visualizations for high dimensional marketing data consisting of up to 100 variables of 25,000 to half a million clients. The goal of the visualization approach in their paper was to present the complex data sets so that patterns are clearly highlighted. Elvins et al. [27] developed a visualization called Worldlets. This tool modifies 3D webs by using 3D thumbnails, and it was inspired by the success of text or image thumbnails in text-based websites. Wordlets was designed to assist users in navigating in the 3D environments by providing 3D information of the regions ahead. Hyperbolic trees [56] were developed to improve the traditional hierarchy visualization. Instead of partially showing a hierarchy when the display region is not large enough, hyperbolic trees display a region of interest in the center of a circular display while other regions are displaced to the edges of the display.

This approach to the improvement of visualization comprehension allows the rapid creation of innovative visualizations. However, there are two major limitations in this approach:

(1) solutions are not easily generalizable since improvements are designed to meet specific requirements, and there is no guarantee that an improvement in visualization comprehension will be achieved, and (2) the impact of the visualizations in a potential population of users is unknown given that these kind of studies do not provide information on why the improvement works.

3.4.3 User-Study based Visualization Improvement

The scientific visualization community recognized the need to incorporate user studies as an integral part of the evaluation process [54]. There are several areas of research where well established visualization problems have been identified and user studies have helped researchers to understand the nature and the cause of those issues. Kim, Gorla and Interrante ([51], [54]) studied the effect of different texture patterns in the assessment of shape information by comparing participants' judgments of a 3D surface under different texture patterns and orientation methods. Her research is one of the first systematic evaluations performed on such visualizations. Tory et al. [82] compared performance on 2D, 3D and 2D/3D combination visualizations in tasks that required subjects to estimate orientation and relative position. They found that 3D displays with shadows were more effective for tasks requiring relative positioning. They also found that 2D/3D displays are a better choice for relative positioning than 2D or 3D alone. In terms of orientation tasks, their results suggest that 2D/3D displays are useful for precise orientation while 3D displays are effective for approximate orientation. To make VR navigation easier, Vinson [86] studied the use of landmarks in virtual environments to help users build cognitive maps. He found that even among females, wide navigation skill differences are found and that not only females benefit from support in virtual environment navigation. Benyon and Murray [8] proposed the development of computer systems that adapt to viewers' differences in personality and cognitive styles.

Although user studies are becoming part of visualization evaluations, they are often run using graphics graduate students as subjects making the results applicable only to highly trained experts in the field. Furthermore, the varying degrees of spatial ability in the participants are usually not clearly stated. As shown in Section 3.2.3, the performance of users with low and medium spatial skills may be quite different from expert users, and visualization evaluations that recruit only expert users are likely to miss comprehension problems of large portions of the user population.

3.5 Training and Skill Transfer

There is another key aspect of training, namely “skill transfer”. Skill transfer is defined as the creation of a general or higher level skill or understanding of a task or the application of what is learned in one area to a more general or different area. This is what schools attempt or hope to achieve throughout their curriculum. The focus of this research is to create training in such a way that a more generic type of visualization literacy is developed. Skill transfer is a complex process which is very difficult to achieve. This is especially true because it is very difficult for the trainees to perceive task commonality in the first place. Research has shown that the specific training method and the nature of the task [12] strongly influence whether skill transfer can be achieved. Even more, it has been shown that the specific requirements for the development of an abstracted skill are mass practice, that is, large amounts of practice so that a specific skill is over-learned ([9], [43]) and the right variety in the practice so that the general rather than the specific skill is abstracted ([87], [35]). Thus, although training may not be able to show a general spatial ability improvement, it can be possible to build a skill that will transfer to understanding the task required in the visualization family studied in this thesis so that trainees will be able to comprehend instantiations of visualizations in this family that they have not seen before.

3.6 Chapter Conclusion

The aforementioned research illustrates that variables such as the visualization task, a user abilities, and dimensionality affects visualization comprehension. Since computerization often leaves out multiple cues we use in our everyday world, little is known about what features or lack of features might improve visualizations for users. The long range goal of this research is to evaluate visualization tasks and try to distill out the key properties that look like they increase comprehension difficulty and then to train users in these properties one at a time using multiple and increasingly difficult problem sets until users are able to integrate them and understand relatively complex visualizations.

The next chapter describes, in detail, the visualization comprehension task that has been chosen to create this training. It also outlines the factors that shaped its final design.

Chapter 4
The Visualization Test

4.1 Introduction

The development of visualization literacy involves the study of a large and diverse collection of visualizations. Visualizations have been used since ancient times, in particular, those that depict data with an intrinsic visual-spatial meaning (e.g., maps, medical drawings, architectural drawings). In recent decades, visualizations have been created that represent data with metaphorical or artificial visual-spatial meaning (e.g., graphs, tree-maps and parallel coordinates). The use of computers graphics and human-computer interface technologies has sped up the evolution of visualizations. Techniques such as the use of color, lighting, dimensionality (i.e., 2D or 3D), animation and interactivity are changing the visualizations look and how they are used. From the large spectrum of computer-based visualizations, one particular technique must be selected as the starting point in the study of training methods for the development of visualization literacy.

This chapter discusses the criteria used to select projection visualizations as the focus of study in this dissertation. The discussion then turns to the design of the visualization test and the visualization task in order to measure viewers' visualization skill. The chapter concludes with a discussion of the limitations in the visualization test design.

4.2 Projection Visualization

The visualization that will be studied is based on the use of 2D orthogonal projections to represent 3D objects. This class of visualizations will be called *Projection Visualizations*. Projection visualizations have been applied to numerous fields and have been modified over time to better fit the requirements of viewers and the technological advances. Projection visualizations are

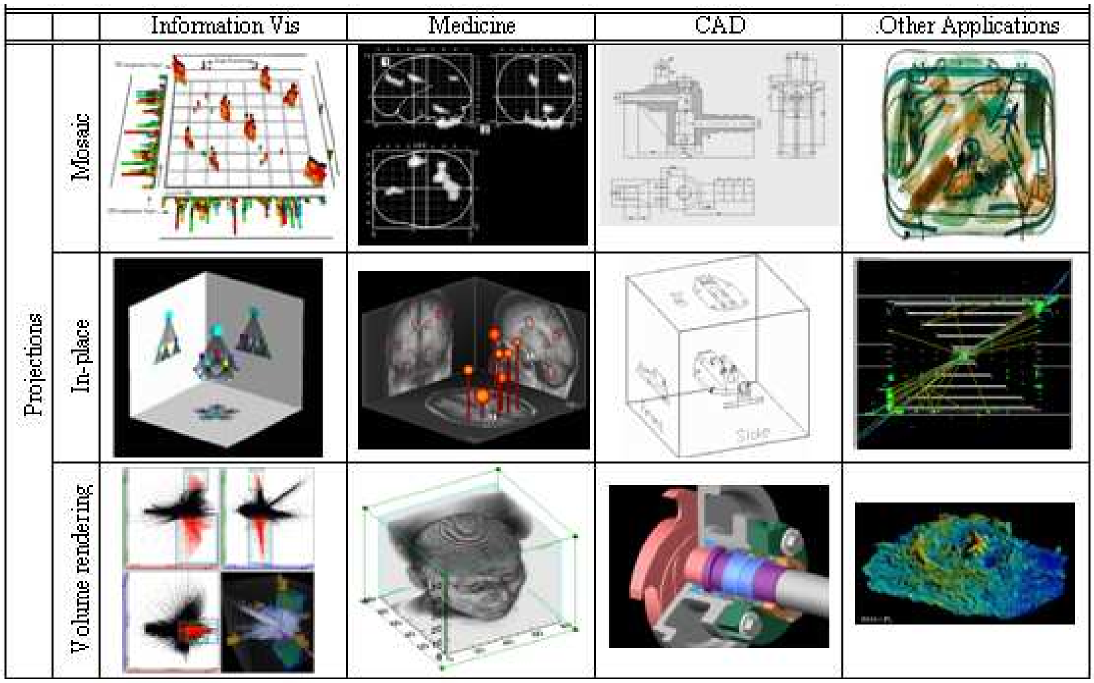


Figure 4.1: Example of visualizations based on compound slices applied to security, medicine and CAD.

used in settings that require intensive training such as radiology, architecture and engineering, where specialized courses are needed to teach students to interpret the images used in their fields. This type of visualization is also used by viewers with little or no formal training, who have developed basic comprehension skills based on familiarity with the visual representations. This is the case of physiotherapists that use visual medical images from X-rays and CTScans to treat patients, as well as viewers with limited previous exposure to this kind of visual representations, possibly those with low spatial skills and only basic training such as security and airport X-ray scanners. Typical projection visualizations are shown in Figure 4.1. The widespread use of projection visualizations and the diversity of the expected viewers make the development of the visualization skill needed to comprehend this visualization even more relevant.

The method of projection used in this research presents orthogonal flat-shaded orthogonal projections. Although improved projection methods are preferred in fully developed visualizations, flat-shaded projections are better suited to reach the goal of uncovering which properties are relevant in the comprehension of projections and how their presence/absence affect visualization difficulty.

4.3 The Visualization Test

The *visualization test* is a series of *visualization questions* that use a simplified version of projection visualization to evaluate viewers ability to reconstruct a 3D object based on 2D projections. The *visualization task* asked from viewers in each visualization question is to analyze three flat-shaded orthogonal projections (back, bottom, and right) and to build a “mental picture” of the 3D object that they represent. Once viewers develop the best possible mental representation of the object, they are asked to select from a set of four 3D objects, the one that best fits the mental image they formed. The visualization task is designed to be simple enough to be used by untrained viewers and to present a significant cognitive challenge to viewers with highly developed spatial skills or relevant previous experience. The task also represents the skill viewers need to have in order ro understand this kinf of visualization.

Each visualization question consists of two screens: the *analysis screen* and *the selection screen*. The analysis screen displays the three orthogonal projections and instructs the participants to form a ”mental image” of the 3D objects based on the 2D projections, paying particular attention to shape and orientation. Once participants consider that they have developed the best possible mental representation of the object, they proceed to the selection screen. In the selection screen, participants are asked to select from a set of four 3D objects, the one that best fits the mental image they formed. The objects in the selection screen can be presented side-by-side (i.e., four objects displayed in one screen) or in sequence (i.e., only one of the four objects is displayed on the screen at any time). The 3D objects in the selection screen are initially shown directly from the front (as illustrated in Figure 4.2), but can be rotated left/right to $\pm 60^\circ$ around the vertical axis, improving a viewers ability to perceive fine orientation differences between 3D objects. Participants can browse back and forth between the four 3D objects before finally selecting an answer. However, they are not allowed to see the 2D projections after leaving the projection screen.

Two visualization question layouts were used for the analysis screen. The first layout is called *mosaic layout*. In the mosaic layout, the analysis screen presents projections side-by-side labeled as back, left and bottom. The selection screen presents the four possible answers simultaneously. The second layout is called *in-place layout* because the projections are displayed in

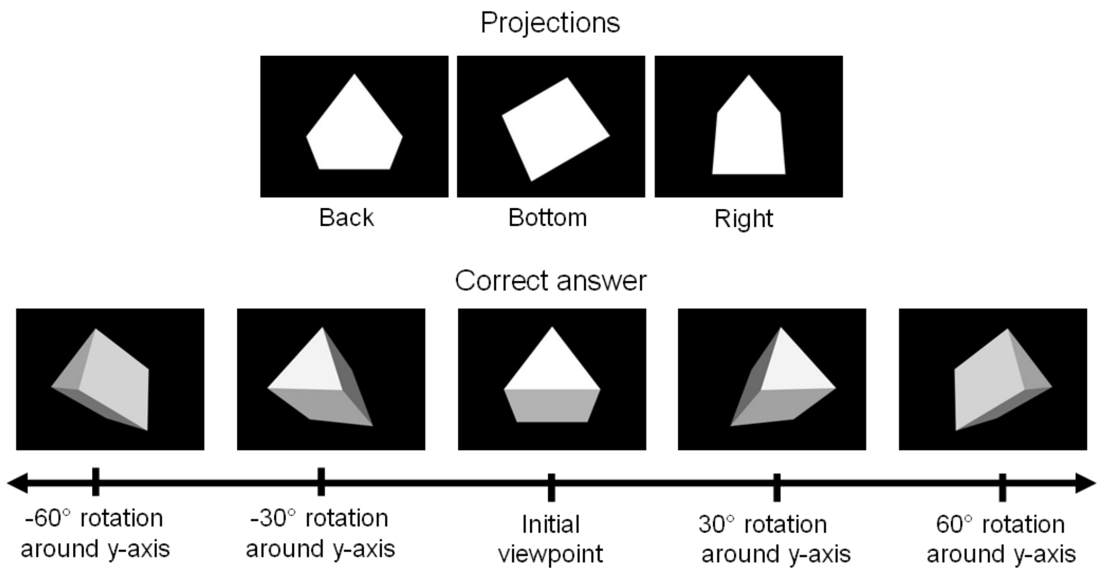
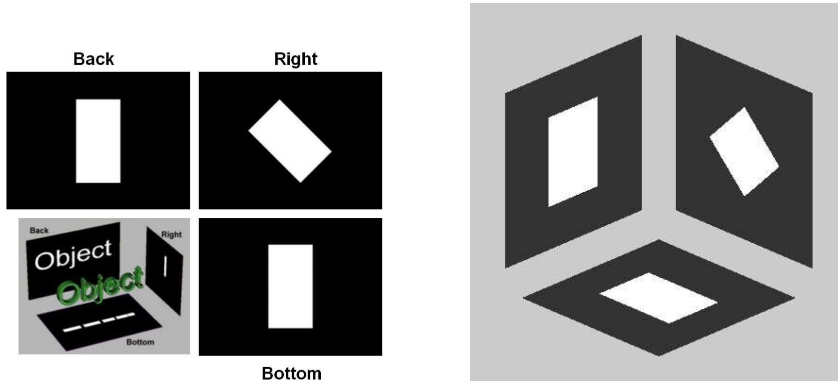


Figure 4.2: Projections and the correct answer in different orientations. The initial viewpoint shows the 3D objects used as answers in the selection screen directly from the front. Viewers are allowed to rotate the 3D object up to 90° left or right.

their corresponding projection planes in 3D space: x-y plane, x-z plane and y-z plane. The selection screen presents the answers sequentially when the in-place layout is used . Figure 4.3 presents the projections of the same object in both layouts. It is important to emphasize that in-place projections and in-place slices are different representations. In-place slices refers to 2D slices presented in the exact spatial position that they would occupy in an object, while in-place projections are projections displayed in a projection plane that is located in the correct position in 3D space as shown in Figure 4.4 .

The 3D objects used in the experiment ranged from simple forms based on geometric icons (i.e., Geons) and realistic looking models of common objects. The geometric objects include cubes, boxes, pyramids, prisms, cylinders, cones, arches, tori, c-shapes and l-shapes. Some of the geometric objects were created by combining two o more geons and they are referred to as compound objects. The following realistic models of common objects were also included in the visualization test. A guitar, a teapot, an hourglass, a chess knight, a telephone, an airplane, a cow, a trumpet, a chair, and a bottle were used. Figure 4.5 shows all the objects used in the experiments that took place as part of this research. Not all objects were used in each experiment and that the order in which they are presented was changed according to the goals



(a) Mosaic (b) In-place

Figure 4.3: Mosaic and in-place layouts applied to a visualization question that presents the projections of a box rotated 45° around the x-axis.

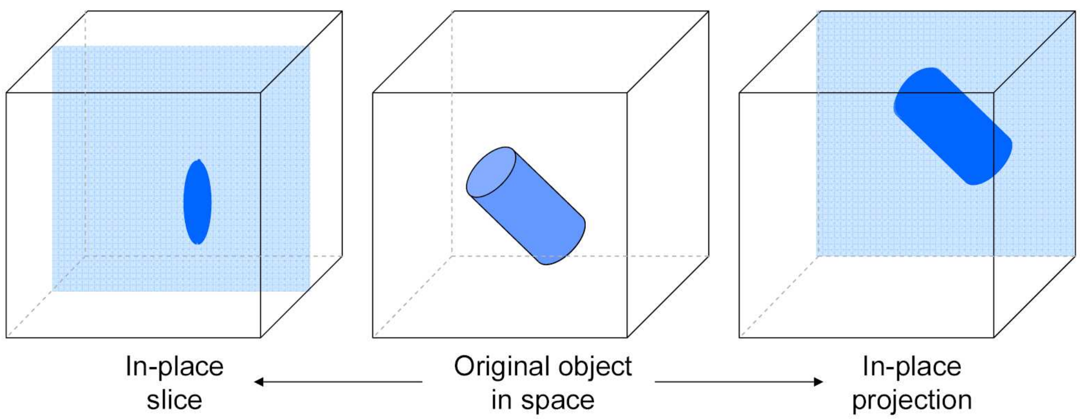


Figure 4.4: Example of in-place slice and in-place projection of a cylinder.

of each particular study.

A strategy similar to Shepard and Metzler [74] was adopted to select the position of the objects in the set of answers. For instance, mirror objects and objects with close angles as false answers were used in the tests. It is important to note that it has been found that commentary on skill level and gender differences in spatial ability can negatively affect subject's performance, the term "spatial ability" and other similar terms were avoided throughout the experiment description, instructions and training.

The visualization test design applied fundamental findings in the study of cognitive and spatial factors. For instance, reports by Just and Carpenter [47] recorded participants' eye movements in the Shepard and Metzler Mental Rotation Task [74] and discovered that their

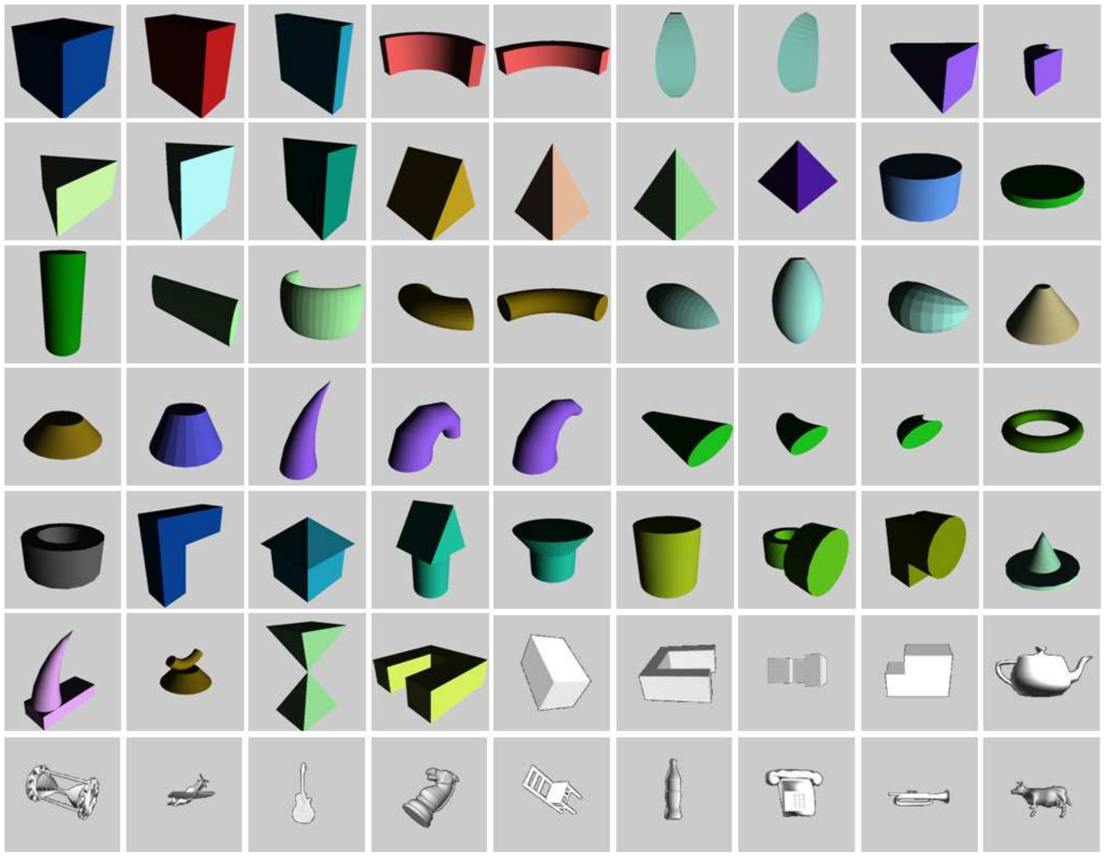


Figure 4.5: Geometric objects and real models used in the visualization test

eyes moved back and forth between the figure to be rotated and the list of answers to choose from. This indicates that the mental task was not merely a mental rotation, but included feature matching between the figures. In order to prevent this "feature matching" behavior, the visualization test was designed so that once the participants finished analyzing the projections and were ready to select the object they had cognitively constructed, it was not possible to re-visit the projections (i.e. separate screens were used for the questions plus answers and one could not switch back from one to the other). Figure 4.6 presents three examples of visualization questions in the in-place layout, as well as the corresponding set of answers.

4.4 The Visualization Task

The visualization test captures the viewers' *visualization skill*, that is, the skill to accurately identify salient visual features, determine conceptual relations between features and to interpret

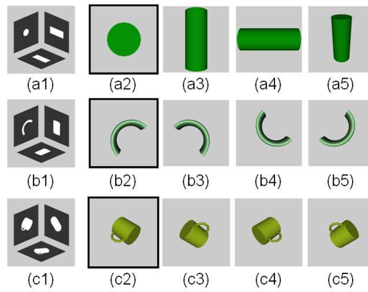


Figure 4.6: Examples of object projections and the set of four possible answers. Objects (a2), (b2) and (c2) are the 3D objects represented by the projections (a1), (b1) and (c1). All the other 3D objects are incorrect answers.

this information to form a coherent representation of the information encoded on the visualization. In the case of the projection visualization, visualization skill implies the identification of salient 2D geometric properties (e.g., edges, corners, general shape, etc.) in the individual projections, the recognition of relations of geometric properties between projections (e.g., corners that appear in more than one projection) and the recognition and reconstruction (if possible) of properties that are not visible, and it allows the reconstruction of the 3D object (or possible objects, if ambiguity exists) represented by the projections by creating relations between 2D geometric properties and the perceived shape and orientation in 3D.

The *visualization task* evaluates viewers' visualization skill by asking for the mental reconstruction of 3D objects based on their 2D flat-shaded projections. Viewers need to therefore, memorize the reconstructed shape and identify the object that best fits their mental representation from a set of four 3D objects where only one answer is correct. Models of shape representation and recognition identify the following properties as descriptors of an object: size, vertical and horizontal position, aspect ratio, coarse and fine orientation, among others. The visualization test focused on the reconstruction of coarse and fine orientation. Compared to 3D renderings, 2D slices and 2D projections have been shown to facilitate the quantification of rotation differences. The visualization test was designed to focus on the accuracy of the reconstruction of coarse orientation (i.e., larger than 45°) and fine orientation (i.e., 45° or less). As shown on Figure 4.6, the four 3D objects in the selection screen have the same general shape, but they differ in their orientation.

Viewers' performance in the visualization task was measured in terms of: (1) accuracy of the answers (i.e., the time spent on the first screen), (2) time spent analyzing the object's projections (i.e., the time spent on the second screen), and (3) time spent selecting the final answer. Given that participants are not allowed to return to the screen showing the projections, the time to analyze the projections should be independent of the time used to select an answer. Although object and shape recognition is a perceptual level task, the visualization skill required to perform the visualization task clearly involves cognitive processes such as memorization, visual-spatial transformations and high-level problem solving skills.

4.5 Limitations of the Visualization Test

One of the limitations of the visualization test is that the only shape-describing property evaluated in the visualization tests was the angle of rotation of the 3D object with respect to the X, Y and Z axes. It was not known what effect the choice of angle would have on the visualization comprehension. Instead of selecting a large sample of angles, two subsets were selected, coarse rotations (e.g., 75°, 90° and 180° rotations), and fine rotations (e.g., 15°, 30° and 45° rotations). When this study was conducted, it was not known that humans are poor at estimating small angle differences. Thus, one limitation is that data was lost because of the addition of the 15 degree rotation which reflects a different skill than visualization comprehension.

The inability to re-visit the projections after leaving the analysis screen may impact performance in the visualization test due to memorization ability. The Visual Memory test (Shape Memory Test MV-1) is used to measure the impact that memorization has on the performance of viewers. The correlation between the tests scores and accuracy in the visualization test will capture the effects of memorization requirements in test takers, which will help determine how important this factor is.

The view-point discrepancy between the projections in the in-place analysis screen layout and the 3D objects in the selection screen may have a negative impact on the visualization test takers. One may argue that, in this case, after the object is reconstructed, it needs to be mentally rotated to match the view point of the possible answers. This statement is based on the assumption that the mentally reconstructed object is view-dependent. Whether the reconstruction and interpretation of 3D objects is view-dependent or not is still a topic of debate in the psychology and cognitive science community. Therefore, any effect of the in-place representation on the visualization test will contribute to unexplained variability in the data.

Another limitation of the visualization test is the choice of rendering that was used both on the projected objects and the answers. A choice has to be made, but this precludes studying other possible choices. Choices were made to represent the common ways in which the projection visualization is typically used. All choices were not explored because this would extend the experiment per subject to an unreasonable length, and because the key focus of the research was on teasing out the comprehension properties rather than exploring rendering. Only flat rendering was used on the projections and in the answers although statistical parametric mapping or wire frame rendering could be an alternative to be explored at some other time.

Several interactive and 3D visualizations are available as alternative analysis tools. However, the use of 2D projections in these fields is unlikely to be completely replaced by 3D renderings because projection visualizations facilitate the precise judgment of spatial relations such as rotation and proportion. Furthermore, static projection visualizations form the basis of figures in textbooks, scientific journals, newspaper articles, etc.

The final limitation in the design of the visualization test was the forcing of mental reconstruction to avoid pattern matching strategies. In a real visualization comprehension task there is not a complete mental image formed, but only a partial image which is then supplemented with pattern matching (i.e., the pattern matching effect found in the Shepard and Metzler Mental Rotation test [47]). Requiring a complete mental image before the subject views the answer set may easily exceed the short term memory of a subject where such a mental image would be held. For complex objects, this short term memory can easily be exceeded especially if the objects are unfamiliar to the subject.

4.6 Chapter Summary

The development of visualization literacy begins by studying salient visual comprehension aspects related to visualization techniques. This chapter presented fundamental concepts related to the visualization that will be studied and the instruments that will be used to study it. These concepts are:

1. *Projection visualization*: these are a class of visualizations that use of 2D orthogonal projections to represent 3D objects.

2. *Visualization question*: A visualization problem that requires interpretation of a visualization followed by the selection of an answer by the viewer. The visualization questions used in the user studies that are part of this dissertation are a simplified projection visualization based on 2D flat-shaded projections.

3. *Visualization task*: The comprehension task asked from test takers in each visualization question. Visualizers are asked to create a mental picture of the 3D object represented by the 2D projections. Viewers are asked to pay attention to the object's shape and orientation. Then, they are asked to select from a series of 3D objects the one that is closer to their mental image.

4. *Visualization test*: Series of visualization questions. The visualization test was developed to capture the visualization skills of test takers. The visualization test allows the capture of three metrics: (1) accuracy of the answers, (2) time spent analyzing the object's projections, and (3) time spent selecting the final answer.

5. *Visualization skill*: These are skills required to comprehend the visualization questions accurately. This skill implies (1) the identification of salient 2D geometric properties (e.g., edges, corners, general shape, etc.) in the individual projections; (2) the recognition of relations of geometric properties between projections (e.g., corners that appear in more than one projection) and the recognition and reconstruction (if possible) of properties that are not visible; and (3) the reconstruction of the 3D object (or possible objects if ambiguity exists) represented by the projections by creating relations between 2D geometric properties and shape in 3D.

The following chapter presents an overview of the three experiments that are part of this dissertation and describe how the visualization test was used to explore different aspects of visualization literacy related to projection visualizations. Chapter 6 and Chapter 7 describe a study designed to determine the relationship between viewers' spatial abilities and their visualization skill as well as to identify geometric properties that make visualizations difficult to comprehend. Chapter 7 also describes a verbal protocol study were participants were asked to talk aloud while they analyzed the visualization questions in order to capture information about their problem solving strategies. Finally, Chapter 8 describes a study designed to determine if training individuals by introducing the properties that were found to increase comprehension difficulty one at a time will improve their visualization comprehension better than individuals who are not trained in this fashion. Chapter 9 concludes this dissertation.

Chapter 5
Overview of Experiments

5.1 Introduction

The framework for the development of Visualization Literacy which is evaluated in this dissertation consists of three consecutive steps. Each step requires different data in order to understand the different factors that affect visualization comprehension. As shown in Figure 5.1 three experiments were designed and conducted: Study 1, Study 2, and Study 3.

Study 1 was designed to measure an individuals' cognitive abilities and to uncover how well these abilities correlated with their ability to comprehend the projection visualization. Visualization comprehension was measured by three traditional measures (i.e., accuracy of the answers, time spent analyzing the visualization question and time spent selecting an answer). The data captured in Study 1 was subject to two different analyses: One analysis focused on determining the correlation between cognitive abilities and visualization comprehension, and the second was an exploratory analysis geared to finding out what visual properties of the visualization increased their difficulty. Study 2 is a verbal protocol analysis in which participants were asked to verbally describe their strategies while they performed the visualization test. The results from the visual properties analysis and the verbal capture of participant's strategies are used in Step 2 to identify the candidate visualization properties believed to make visualization comprehension difficult. Study 3 measures the effect of training participants by ordering the properties found to affect visualization comprehension. Participants were assigned to two groups and were trained using the same visualization questions, but the order in which the questions were presented either random or grouped by property type with the easiest properties presented first. If the properties that affect visualization comprehension have been truly identified, the grouping and ordering should improve training so that this group of study participants will outperform the other in the visualization questions.

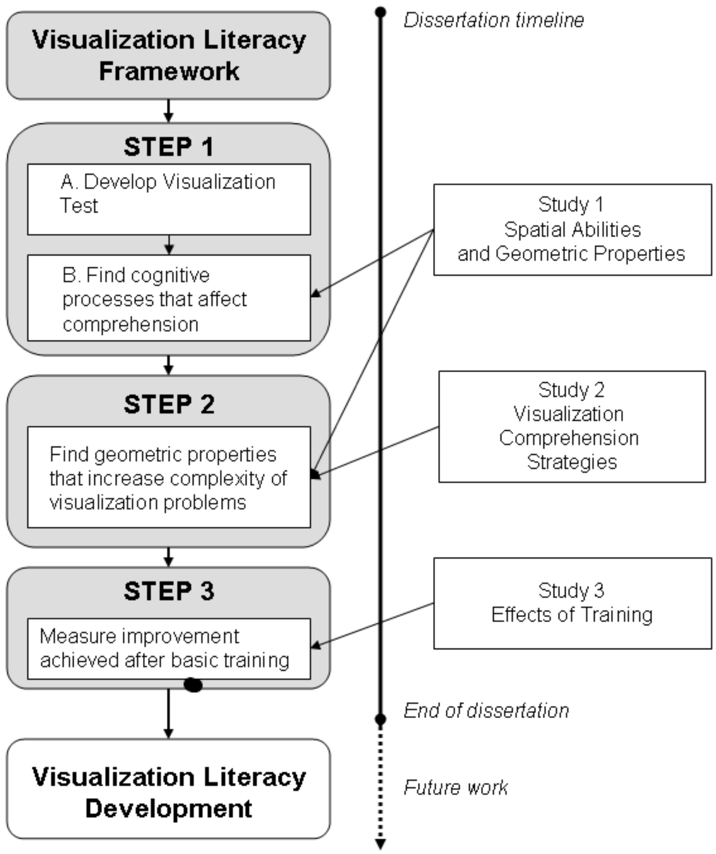


Figure 5.1: Overview of the three experiments performed in this dissertation in relation to the three steps that form the research approach for the development of visualization literacy training

This chapter presents an overview of the three experiments including independent and dependent variables, method of analysis, number of subjects, description of the visualization questions and the visualization test.

5.2 Study 1: Spatial Abilities and Geometric Properties

Study 1 was designed to capture the correlation between the cognitive abilities of the visualization viewer and his or her ability to accurately comprehend the projection visualization. Participants were asked to answer a sequence of visualization questions , as well as a to take set of five cognitive abilities tests.

The visualization comprehension of experiment participants was captured with three measures to quantify the performance in the visualization test. These are the dependent variables in this study: Accuracy of question answer (0 - incorrect, 1 - correct), time of analysis (i.e., time spent by participant analyzing the projection) and time of selection (i.e., time it took the participant to select an answer). The independent variables are gender (male or female) and level of spatial ability (low, medium and high). Spatial ability was measured using a set of five cognitive factors. These factors were selected because previous studies found them to be correlated to comprehension difficulties in various visualizations. Each cognitive factor was evaluated by means of a paper-based test from the ETS Kit of Factor-Referenced Cognitive Tests [26].

A total of 28 males and 28 females participated in this experiment. They answered 38 visualization questions that were presented in one session. The visualization questions were presented in mosaic format and the possible answers were presented simultaneously on a following screen. The objects used as stimuli were single and compound geometric shapes and realistic models of common objects.

The data collected in this study was analyzed twice. The first analysis, presented in Chapter 6 focuses on finding the cognitive skills that affected the comprehension of the projection visualizations. Chapter 7 contains the results of an exploratory analysis aimed at uncovering the visual properties of the visualization questions that make projection visualizations difficult to comprehend.

5.3 Study 2: Visualization Strategies

Study 2 captures the strategies and visual properties that visualizers use to create a mental representation of the 3D objects represented by the 2D projections. Participants were asked to answer a sequence of visualization questions, while they describe aloud the thinking process and the information they used to create a mental image of the 3D object represented by the 2D projections.

The only measure of performance in the visualization test was accuracy of the answer (0 - incorrect, 1 - correct). The verbal descriptions given by participants were videotaped and later transcribed. Participants also took the Paper Folding Test [26].

Five participants took part in the experiment session where they were asked to solve the 38 questions used in Study 1. The visualization questions followed the mosaic format and subsequent simultaneous presentation of the answers. Participants were asked to describe their thought process, the information they were looking at and their conclusions while analyzing the 2D projections.

The videos and transcripts collected in Study 2 were qualitatively analyzed. Verbal descriptions of the properties used to solve the problems and the general problem-solving strategies used by participants are of particular interest in this analysis. The results from this study are presented in Chapter 7.

5.4 Study 3: Effect of Training

Study 3 was designed to test the effect of a basic ordered incremental training that presents visualization questions in increasing order of difficulty. The difficulty of each visualization question is determined using the properties that were found to correlate to viewers' comprehension accuracy. The incremental training is based on the gradual introduction of the geometric properties found to increase visualization difficulty discussed in Chapter 7. The incremental training was expected to improve the comprehension of the fundamental spatial-reasoning processes involved in the analysis of a projection visualization. Since all training leads to learning, the issue addressed here is whether the learning modules created in the structured training lead to better learning. If it does, then the properties and strategies selected in Study 1 and Study 2 have support for their validity. That is, if the structured training was not better than random training then the organization of the properties selected would have no effect and therefore, the properties proposed as causing difficulty would not be correct. Also notice that the other main interest is that this learning more quickly leads to a general set of skills in visualization comprehension. It is expected that any type of training will improve a viewers' comprehension of visualizations because practice always causes learning. However, the focus on the properties that cause difficulty and a variable presentation of problems using restricted set of these problems should cause an abstracted type of learning and a more general skill set given that is known in education literature (see Chapter 2.)

Learning is evaluated in two ways. First, the structured learning is compared to learning with similar training that does not involve the structuring of the problems from easy to hard.

Thus, the control group will be presented with the same problems but with those problems being presented randomly. Second, the distribution of the wrong answers to each of the problems is analyzed. If the participants are learning something that is more abstract and general for solving visualization problems, it can be expected that their answers, even the wrong ones, will represent this skill transfer.

Forty-four students (20 females and 24 males) took part on the study. An equal number of participants was assigned as matched pairs on spatial ability to the incremental training and the unstructured training. This study consisted of five experiment sessions that were scheduled 1 to 3 days apart. Forty-nine objects, including single geons and objects composed only 2 or 3 geons were used to create 98 distinct visualization questions. Some of the questions appeared multiple times during training in different experiment sessions.

5.5 Chapter Summary

This chapter presented an overview of the three studies that were carried out as part of this dissertation. It also explained how the analysis of the data collected in the experiments fits in the three step methodology proposed by this dissertation. Figure 5.2 summarizes the experiment design of the studies.

The next chapter describes Study 1 in detail. It includes a description of the task given to the experiment participants, the experiment setup and hypotheses. It also presents the results from the analysis of the correlation between cognitive abilities and visualization comprehension. This analysis constitutes Step 1 of the methodology for the development of a methodology for training visualization literacy.

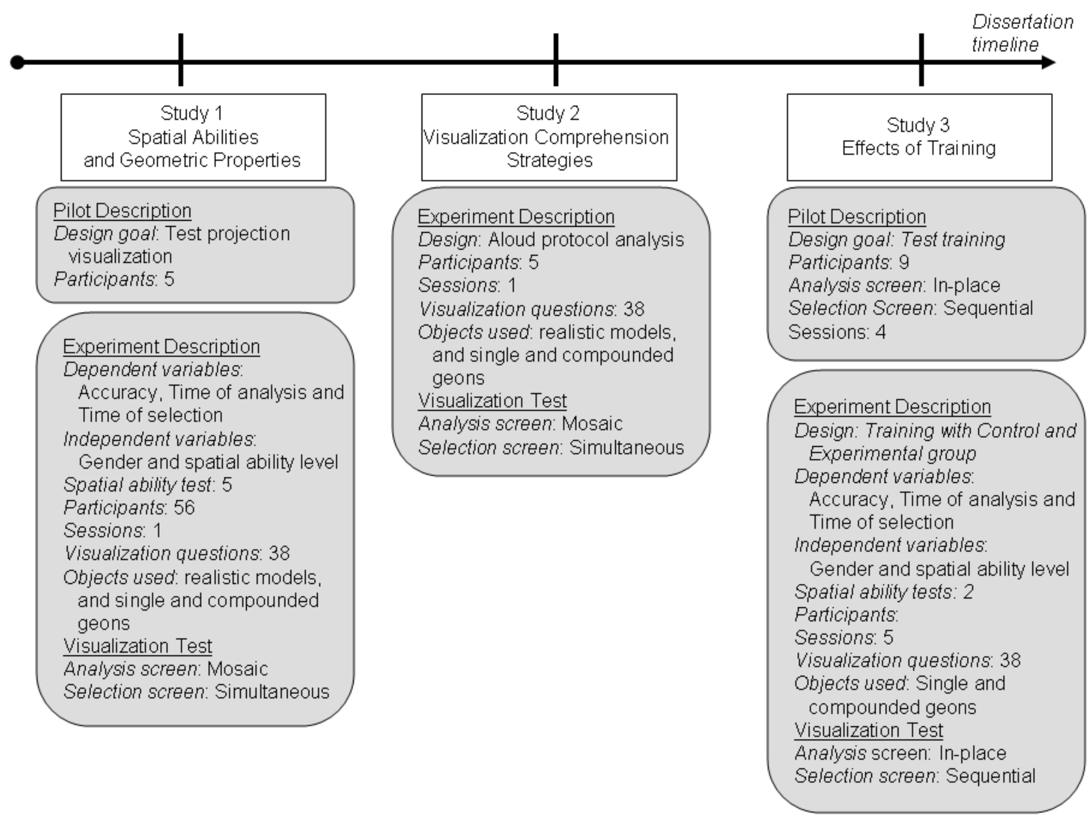


Figure 5.2: Research time line with a brief description of the studies conducted as part of this dissertation and a brief description of the experiment design

Chapter 6

Step 1 - Cognitive Factors that Affect Visualization Comprehension [1]

6.1 Introduction

Numerous studies have reported that low scores in some psycho-metric tests of cognitive abilities are correlated with the difficulty people have understanding many visualizations [2] [79] [22]. Although these studies showed significant effects, in particular, for visual-spatial abilities, most of them have significant limitations. In most cases, the studies used only one test to measure general spatial skills, ignoring the fact that spatial ability is really a combination of multiple skills. Other limitations of these kind of studies includes the lack of cognitive skill diversity of the experiment participants and the lack of in depth data analysis beyond simple correlations.

Study steps back from studies that presuppose possible visualization properties that might impact comprehension. Instead, spatial skills and visualization comprehension are measured in a "fundamental" visualization task and the relationship between these variables assessed. The data collected in this experiment is analyzed in two chapters of this thesis. This chapter presents the results related to the correlations between spatial abilities and visualization comprehension, and Chapter 7 presents the results of an exploratory analysis that uses the results from this chapter to uncover the visualization properties that may affect comprehension difficulty and to quantify the difficulty of visualization questions.

This chapter begins with a description of the experiment design. This includes information

[1] Parts of this chapter were published on the paper: Maria Velez, Deborah Silver, Marilyn Tremaine. Understanding Visualization through Spatial Ability Differences. Proceedings of Visualization 2005. IEEE, pages 511-518. Minneapolis, Min. 23-28 Oct, 2005.

regarding the experiment participants, the experiment setup and the task asked from participants. Expected results and hypotheses are formulated and discussed. The chapter continues with the presentation of the results obtained with regards to visualization comprehension and spatial ability. The chapter concludes with an analysis of the results and a summary of the chapter.

6.2 Pilot

6.2.1 Task and Stimuli

The pilot test used visualization questions with a mosaic layout where the orthogonal projections are shown side-by-side. Participants were asked to analyze the projections and build a "mental picture" of the object. Four possible answers were displayed simultaneously on the screen and participants selected the object that best resemble their mental representation. The orthogonal projections and the set of answers were presented on separate screens and participants were not allowed to go back and forth between screens. The four 3D objects displayed as answers could be rotated (on screen) ± 30 degrees around the vertical-axis. Figure 6.1 presents an example of the visualization questions format and Figure 6.2 shows the objects used.

6.2.2 Participants, Experimental Setup and Procedure

Fourteen graduate students (3 males and 11 females) volunteered to participate in the pilot study. Participants were enrolled in the Information Science, Electrical and Computer Engineering, and the Mechanical Engineering programs. After reading the experiment description, participants were given a demographic questionnaire. They proceeded to take five paper-based cognitive factor tests: Shape Memory Test (CF-2), Cube Comparison Test (S-2), Paper Folding Test (VZ-2), Hidden Patterns Test (CF-2) and Identical Figures Test (P-3). Then, participants took the Visualization Test. They were allowed to take as much time as needed to 60 answer 30 visualization questions.

Performance on the Visualization Test was measured in terms of (1) the accuracy of the answers, (2) the time spent analyzing the three orthogonal projections and (3)the time to select an answer from the set of four possible answers. These variables will be referred as Time of

Table 6.1: Descriptive statistics of participants' score in the tests of cognitive factors. The score is computed by subtracting a fraction of the incorrect answers from the count of correct answers.

Test	Mean	Std. Dev	Min	Max
Shape Memory Test	20.64	11.13	-10.00	31.00
Cube Comparison Test	13.85	14.51	-16.00	37.00
Paper Folding Test	12.01	4.94	2.25	20.00
Hidden Patterns Test	210.31	60.33	60.00	262.00
Identical Figures Test	44.00	97.00	16.22	68.3571

Table 6.2: Descriptive statistics of participants in Visualization Test given during the pilot study

Variable	Mean	Std. Dev	Min	Max
Time of Analysis (sec.)	23.85	10.04	6.37	44.06
Time of Selection (sec.)	18.90	7.80	7.50	37.27
Accuracy (%)	58.57%	15.83%	40	90%

Analysis - ToA (time spent studying projections), Time of Selection - ToS (time selecting an answer) and Accuracy of the participants' answer - Acc. The cognitive ability test were scored using a traditional scoring method that adjusts the scores assuming that guessing can occurs by subtracting a fraction of the incorrect answers from the count of correct answers.

6.2.3 Results

Participants and Cognitive Abilities

The age of participants in this pilot study ranged between 24 and 57 years old, with an average of 34 years of age. It was found that participants have used computers for at least 6 years, averaging 15 years of experience. The scores of the cognitive abilities tests are shown on Table 6.1. The negative scores are the result of a high number incorrect answers in the test and low positive scores can be the result from slow but accurate test taking or fast yet inaccurate answers.

Visualization Test Performance and Correlations

Table 6.2 presents the mean, range and standard deviation for the three dependent variables Time of Analysis (seconds), Time of Selection (seconds) and accuracy (percentage).

A correlation analysis between variables of performance in the Visualization Test and the scores in the tests of cognitive ability found significant positive correlation between accuracy and the scores in the Cube Comparison Test (r = .698, p $<=$ .005) and the Paper Folding Test (r = .647, p $<=$ .012). No correlations were found between time variables and the scores in the tests.

6.2.4 Implication of Results

The results from this pilot study prompted the following modifications:

- The time to answer the visualization questions in Study 1 was limited to 60 minutes which, according to the results in the pilot, should give enough time to participant to answer more than 40 visualization questions.
- Comments made by participants after the test indicated the need to add a display with the number of questions left to answer in the visualization test. Participants also expressed it was difficult to see the shape of the 3D answer objects given the limited rotation to the right and left. The angle of rotation on Study 1 will be increased to $\pm$90 degrees
- A single score in the cognitive ability tests cannot capture the differences in accuracy and test-taking speed. To better understand the performance differences in these test, correct answers, incorrect answers ant total number of answer in the test all need to be measured independently.
- The most common object used in visualization questions with low accuracy was selected to be introduced multiple times on Study 1. The object selected was a prism. It is expected that learning effects can be captured with this method.

6.3 Study 1 Design

6.3.1 Task

The visualization test described in section 4.3 with a mosaic layout in the visualization was used in this experiment. The three orthogonal projections (back, bottom, and right) are displayed in mosaic format and the four answers were displayed simultaneously on the screen. For the participants, the objective of the test was to analyze the projections and build a “mental picture” of the object.

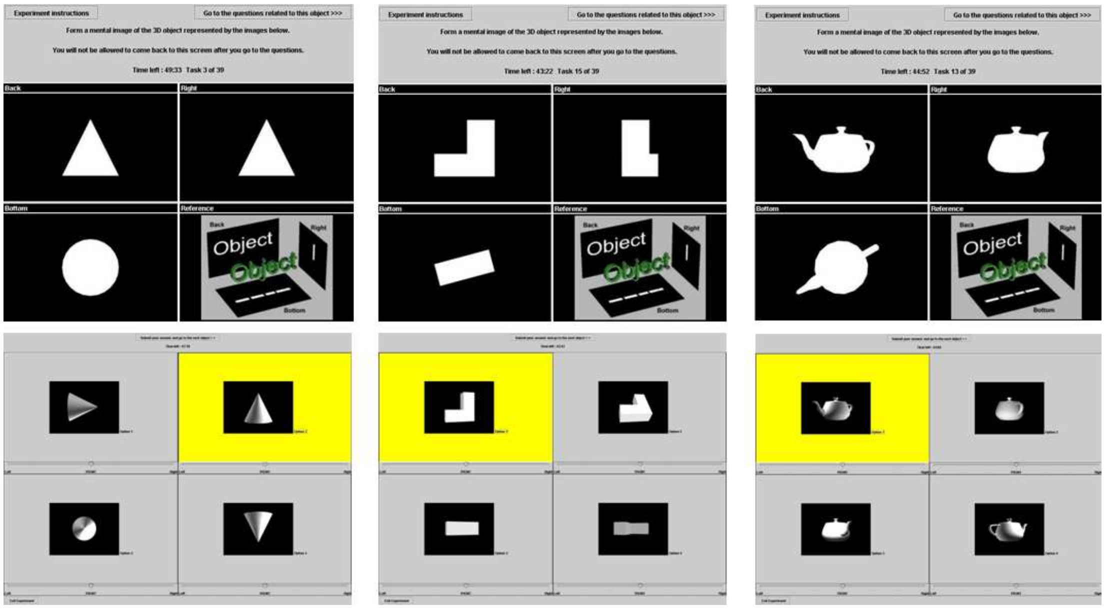


Figure 6.1: Three examples of objects used in the mosaic Projection Visualization Test. The figures at the top show the orthogonal projections. Below the top figures are the four answers. The correct answer appears highlighted. Figures a) and b) are geometric objects and c) is a realistic object. Subjects first view the projection screen, then the answer screen

Participants were then asked to select the imaged object from a set of four possible objects that varied in orientation. Only one of the four answers was correct. Figure 6.1 illustrates three examples of object projections and their associated answers. Note that all the answers present the same object with a different rotation and that realistic and geometric objects were used in this experiment. The subjects where shown the projections and then asked to form a mental image before continuing on to the next screen where the four possible answers are shown. They were not allowed to go back to the projections. However, the four possible answers could be rotated (on screen) ± 60 degrees around the vertical-axis.

6.3.2 Stimuli

The visualization test had 38 visualization questions that used the set of 29 objects shown in Figure 6.2. Nineteen objects were based on geometric icons and ten represented common real objects. The real objects where interspersed with the geometric ones. In order to capture learning in this experimental setup, the L-shaped object (last object of the fourth row on Figure 6.2 was introduced 9 times throughout the experiment in different rotations. All objects were

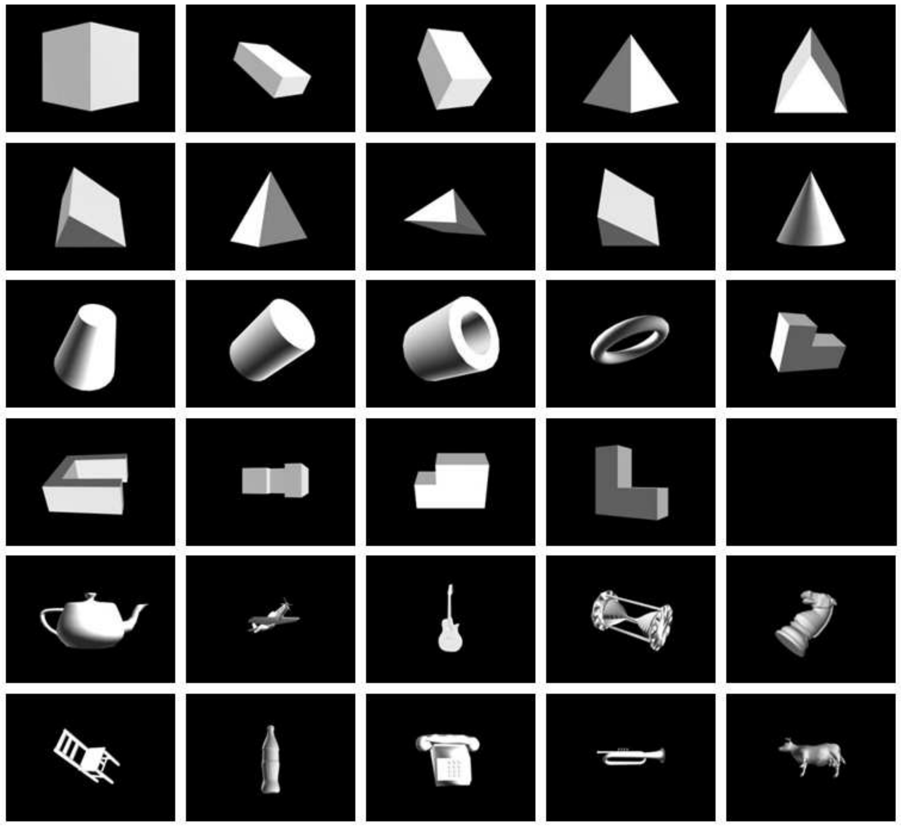


Figure 6.2: Set of 29 objects: 19 abstract objects based on geometric icons and 10 objects that resemble common real objects. These objects were used in the visualization test of Study 1. The last object in row four was introduced several times throughout the experiment in different rotations in order to capture learning effects.

categorized as easy, medium and hard so that the easy objects were presented at the beginning of the tests and the difficulty level was increased as the test advanced. This categorization was based on the perceptual judgment of the experimenters.

6.3.3 Participants

Since the results of this experiment are expected to provide an insight into the comprehension problems that affect users, it is necessary to broaden the range of spatial abilities of the participants in this experiment. Differences in gender and previous spatial experiences increase individual differences in spatial abilities. To this end, participants were recruited through an advertisement posted on the four campuses to attract different students from several departiments at Rutgers University, New Brunswick. Participants from both genders were solicited and no particular computer expertise was required from them.

Fifty-six graduate and undergraduate students from Rutgers University, New Brunswick campus participated in this study. Half of the participants recruited were females. All subjects were paid with a USB drive for their participation in the two-hour experiment. Participants were also included in a raffle of an Apple iPod mini that took place after the experiment concluded.

After reading the experiment description and the subject consent form, the participants filled in a basic demographic questionnaire concerning the subject's field of study, computer background and video game playing experience.

6.4 Method

As mentioned previously, the participants in this experiment were asked to analyze the 2D projections and build a 'mental picture" of the 3D object represented by the projections. They were asked to pay attention to properties as shape and orientation of the 3D object. Participants were then tested on their ability to accurately and efficiently reconstruct and extract information about the 3D object represented by the 2D projections. The dependent variables in this experiment are:

- Accuracy: accuracy of the answer given by participants (correct or incorrect)
- Time of Analysis: Time to analyze the three orthogonal projections (in seconds)
- Time of Selection: Time to select an answer from the set of four answers (in seconds)

Gender and factors of spatial abilities were defined as the independent variables. Five factors of cognitive and spatial ability were measured with the following standardized paper-based tests:

- Spatial Visualization: Paper Folding Test (VZ-2)
- Visual Memory: Shape Memory Test (MV-1)
- Perceptual Speed: Identical Figures Test (P-3)
- Disembedding: Hidden Patterns Test (CF-2)

- Spatial Orientation: Cube Comparison Test (S-2)

To quantify the results of the spatial ability tests, counts of correct and incorrect answers as well as five other scores were used:

- Percentage of correct answers in all test questions (PCT)
- Percentage of correct answers in all answered questions (PCA)
- Percentage of incorrect answers in all test questions (PIT)
- Percentage of incorrect answers in all answered questions (PIA)
- Guess-adjusted (GA)

Given that all the tests of cognitive abilities used here are time constrained, the scoring methods are affected differently by the participant's speed. For instance, the percentage of correct and incorrect answers in all the test questions is affected by the number of questions left unanswered, therefore conveying not only the participant's accuracy but also his or her speed. The percentage of correct and incorrect answers in all answered questions reflects only participant's accuracy. The guess adjusted score is a traditional formula for computing the score that accounts for a participant's guessed answers by subtracting a fraction of the incorrect answers from the count of correct answers.

6.4.1 Procedure

This study was run in groups consisting of 6 to 14 subjects. Each experiment session took approximately two hours. Participants were seated at desks in a computer-equipped classroom. During the first hour, participants were given five paper-based cognitive factor tests: Shape Memory Test (CF-2), Cube Comparison Test (S-2), Paper Folding Test (VZ-2), Hidden Patterns Test (CF-2) and Identical Figures Test (P-3). The paper-tests were distributed one at a time, always in the same order, and using the same procedure. Subjects were given as much time as needed to read the instructions.

After the paper tests, the computer-based Projection Visualization Test was administered. Subjects were seated in front of desktop computers on which the orthogonal projection test was displayed. Subjects were given as long as they needed to read the instructions and ask questions. When they were ready, they completed five practice questions that represented the range of tasks they would encounter and then proceeded to perform the test. They were given 60 minutes to complete 38 questions. At the conclusion of the study, subjects received a debriefing statement explaining the purpose of the experiment.

6.5 Hypothesis and Expected Results

Regarding the correlations between the five cognitive factors and visualization comprehension (measured by accuracy and time), the hypotheses are:

[*H3*] There will be a significant positive correlation between scores on the Shape Memory Test and Projection Visualization Accuracy.

[*H4*] There will be a significant positive correlation between scores on the Shape Memory Test and Projection Visualization Comprehension Time

[*H5*] There will be a significant positive correlation between scores on the Cube Rotation Test and Projection Visualization Accuracy.

[*H6*] There will be a significant positive correlation between scores on the Cube Rotation Test and Projection Visualization Comprehension Time.

[*H7*] There will be a significant positive correlation between scores on the Paper Folding Test and Projection Visualization Accuracy.

[*H8*] There will be a significant positive correlation between scores on the Paper Folding Test and Projection Visualization Comprehension Time.

[*H9*] There will be a significant positive correlation between scores on the Identical Figures Test and Projection Visualization Comprehension Time.

[*H10*] There will be a significant positive correlation between scores on the Hidden Patterns Test and Projection Visualization Accuracy.

[*H11*] There will be a significant positive correlation between scores on the Hidden Patterns Test and Projection Visualization Comprehension Time.

In addition to predicting the correlations between the spatial abilities measured by the various spatial ability tests and the visualization comprehension accuracy and time, some abilities were predicted to be more highly correlated with the visualization selected than others. Because the Cube Rotation test required people to mentally transform an object, this was believed to be more highly correlated than either the Hidden Patterns Test or the Shape Memory Test both for visualization comprehension time and visualization accuracy. The Paper-Folding test also required mental manipulation of an object and was thus, considered to be more highly correlated to visualization comprehension time and accuracy. It is predicted that:

$$\begin{aligned}(Cube\_Rotation_{correlations} &\approx Paper\_Folding_{correlations})\\ &\gg (Shape\_Memory_{correlations}\\ &\approx Pattern\_Matching_{correlations})\end{aligned}$$

Where ”$\gg$” means significantly higher correlations and ”$\approx$” means ”no significantly different correlations. The next set of hypotheses indicates this:

[*H12*] Correlations of the Paper Folding Test Scores with Visualization Accuracy will be significantly higher than Correlations of the Shape Memory Test Scores with Visualization Accuracy.

[*H13*] Correlations of the Paper Folding Test Scores with Visualization Comprehension Time will be significantly higher then Correlations of the Shape Memory Test Scores with Visualization Comprehension Time.

[*H14*] Correlations of the Cube Rotation Test Scores with Visualization Accuracy will be significantly higher then Correlations of the Shape Memory Test Scores with Visualization Accuracy.

[*H15*] Correlations of the Cube Rotation Test Scores with Visualization Comprehension Time will be significantly higher then Correlations of the Shape Memory Test Scores with Visualization Comprehension Time.

Spatial ability differences have been found to be sharply differentiated between males and females. As pointed out by Weiss et al. [90], there are many confounded variables in the origin of gender differences in spatial abilities. There are social and cultural influences, as well as biological differences. Men have been found to have higher mean scores than females in most of the spatial factors mentioned in Chapter 3.3, except for certain Spatial Memory tests. Spatial Orientation, Spatial Memory and Targeting show strong gender differences (approaching an effect size of 1). Disembedding, Spatial Visualization and spatial perception show more moderate differences (effect size of about 0.5).

With this in mind, *it is anticipated to find gender differences in the psychometric test for the Spatial Orientation and Spatial Visualization factors, as well as gender performance differences in the Projection Visualization Test.*

Also, it can be expected that *all five cognitive factors are related to visualization comprehension (accuracy and time).*

The hypotheses regarding gender differences in visualization comprehension are formulated as follows:

[*H1a*] Males will be significantly more accurate than females in the Projection Visualization Test.

[*H1b*] Males will have significantly higher scores than females in the Cube Rotation Test.

[*H1c*] Males will have significantly higher scores than females in the Paper-Folding Test.

[*H2*] Females will have significantly higher scores than males in the Shape Memory Test.

6.6 Results

Data was analyzed our data as follows: descriptive statistics (mean, number of subjects, and standard deviations) were computed for men vs. women for the Projection Visualization Test and for each of the spatial ability tests. These spatial abilities measures were compared to

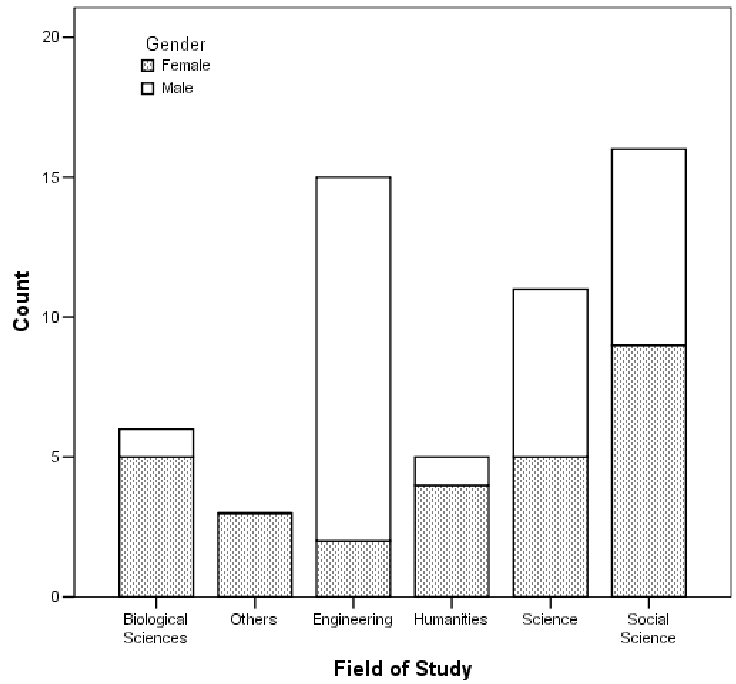


Figure 6.3: Field of study of experiment participants on Study 1. Each bar shows the number of males and females from each field of study. Half of the participants are males

previously known measures captured with a large subject population. The measures found in this experiment were within the expected range indicated by these standards.

6.6.1 Questionnaire Results

Participants' ages ranged from 18 to 31 years with an average age of 21 years (84% were undergraduate students). As shown in Figure 6.3, most participants came from engineering (e.g., mechanical engineering and biomedical engineering), social sciences (e.g., sociology and psychology), and sciences (e.g., physics and computer science). The majority of male participants were enrolled on engineering or science programs.

All participants had about 10 years of experience with computers. Five subjects reported no experience playing video games, but average video game playing experience was approximately 10 years. Most subjects spent less than an hour per week playing video games, but three played more than 10 hours per week.

6.6.2 Cognitive Factors and Performance in the Visualization Test

Descriptive statistics for the psychometric tests were computed: Shape Memory Test (MV-1), Cube Comparison Test (S-2), Paper Folding Test (VZ-2), Hidden Patterns Test (CF-2) and Identical Figures Test (P-3). Table 6.6.2 shows the mean, standard deviation and range for the percentage of correct answers in all test questions (PCT), percentage of correct answers in all answered questions (PCA), percentage of incorrect answers in all test questions (PIT), percentage of incorrect answers in all answered questions (PIA) and guess-adjusted (GA) scores.

As shown in Table 6.6.2, significant gender differences were found on the PCT score of the Hidden Patterns Test (W=277, Z=-1.885, $p<.03$). Tendency towards significance was observed on the PIT score (W=313, Z=-1.309, $p<.08$) and the GA score (W=295.9, Z=-1.582, $p<0.6$) of the Hidden Pattern Test; as well as in the PCT (t=1.393, df=56, $p<0.08$) and GA (t=1.399, df=56, $p<0.08$) scores in the Identical Figures Test. No significant differences gender in performance were found for participants based to their field of study. A Shapiro-Wilk test of normality found that most of the cognitive tests scores were not normally distributed.

Table 6.4 presents the mean, range and standard deviation for the three dependent variables associated with performance: Time of Analysis (ToA), Time of Selection (ToS) and accuracy (Acc). Accuracy scores of male participants were significantly higher than females' (t = -2.673; df = 56; $p < .005$). No significant gender differences were found in analysis or selection time. Time of Selection was found not to be normally distributed (W=858, df=56, $p<.000$).

The effect of learning was also examined. As indicated earlier, one of the objects was presented at eight different angles during the experiment. It was found that there was no clear learning curve in the accuracy of the answers for this particular object. As shown in Figure 6.4, there is a decrease in time to select an answer. Thus, participants indicated a gain in skill in examining and selecting answers, however incorrectly they performed. The percentage of accurate answers given by the participants appears in each question is also shown in Figure 6.4.

6.6.3 Correlation Analysis

A correlations analysis was conducted between the scores in the spatial ability tests of the subjects and their visualization performance scores. Figure 6.5 presents a correlation map

Table 6.3: Descriptive statistics of participants (grouped by gender) in the tests of cognitive factors. Significant gender differences were found only on the Percentage of Correct answers in all Test questions (PCT) score in the Hidden Patterns Test (CF-2)

		Females			Males		
Test	Score	Mean	Std. Dev	Min/Max	Mean	Std. Dev	Min/Max
MV-1	PCT (%)	73.9	10	44.4 - 88.9	70.9	12.3	30.6 - 86.1
	PIT (%)	84.7	10.4	50 - 100	84.1	12.2	52.4 - 100
	PCA (%)	13.4	9.2	0 - 44.4	13.3	9.6	0 - 38.9
	PIA (%)	15.3	10.4	0 - 50	15.9	12.2	0 - 47.6
	GA (Count)	21.79	6.71	0 - 32	20.75	7.32	1 - 30
S-2	PCT (%) [1]	49	18.2	23.8 - 97.6	50.3	17.5	11.9 - 78.6
	PIT (%)	81.1	11.4	60 - 97.6	79.3	15	45.8 - 100
	PCA (%)	11	7.3	2.4 - 31	12.7	10.7	0 - 42.9
	PIA (%)	18.9	11.4	2.4 - 40	20.7	15	0 - 54.2
	GA (Count)	15.96	8.91	5 - 40	15.82	9.84	-2 - 32
VZ-2	PCT (%)	65	15.2	40 - 95	65	13.5	40 - 95
	PIT (%)	85.5	12.6	50 - 100	85.3	11.2	60 - 100
	PCA (%)	11.3	10.8	0 - 50	11.6	10.1	0 - 40
	PIA (%)	14.5	12.6	0 - 50	14.7	11.2	0 - 40
	GA (Count) [1]	12.44	3.31	7.5 - 19	12.42	2.93	7.5 - 18.75
CF-2	PCT (%)	55.1	12.1	37.6 - 85.8	48.2	12	17.3 - 75.3
	PIT (%)	97.4	2.7	88.5 - 100	97.8	2.8	88.5 - 100
	PCA (%)	1.5	1.6	0 - 6.8	10	10	0 - 4
	PIA (%)	2.6	2.7	0 - 11.5	2.2	2.8	0 - 11.5
	GA (Count)	214.46	47.57	149 - 338	188.86	49.05	60 - 299
P-3	PCT (%) [12]	79.8	13.7	47.9 - 99	74.6	14.3	37.5 - 97.9
	PIT (%)	1.9	1.6	0 - 6.3	1.8	1.2	0 - 5.2
	PCA (%)	97.8	17	93.7 - 100	97.7	1.5	94.2 - 100
	PIA (%)	2.2	1.7	0 - 6.3	2.3	1.5	0 - 5.8
	GA (Count) [1]	76.19	12.94	46 - 94	71.21	13.66	35.5 - 93.5

[1] Test scores were found to be normally distributed; [2] Significant gender differences found between males' and females' scores.

Table 6.4: Descriptive statistics of male and female participants in our orthogonal projections visualization. Significant gender differences were found in Accuracy, that is the percentage of correct answers in the visualization test

		N	Min/Max range	Mean	Std. Dev
Accuracy (%)	Females	28	16 - 89	50.75	17.42
	Males	28	32 - 87	61.93	13.63
Analysis Time (Seconds)	Females	28	6.7 - 35.4	22.11	7.91
	Males	28	10.6 - 36.7	21.41	8.13
Selection Time (Seconds)	Females	28	6.2 - 43.1	16.8	9.6
	Males	28	5.7 - 24.3	14.1	4.6

with the results of a correlation analysis between and within performance metrics and all the scores in the cognitive factors tests. Colored areas represent significant correlations with values ranging from -1 (darkest green) to 1 (darkest red). Significant correlations between -0.1 and 0.1, as well as non-significant correlations appear in white. As expected, large correlations can

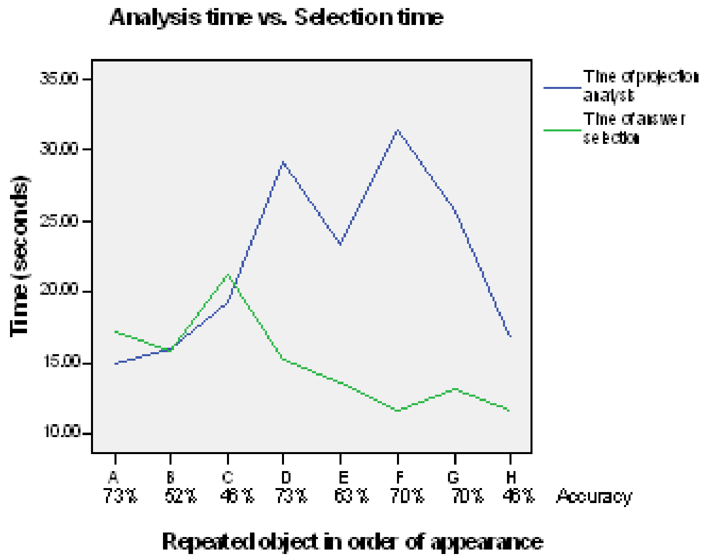
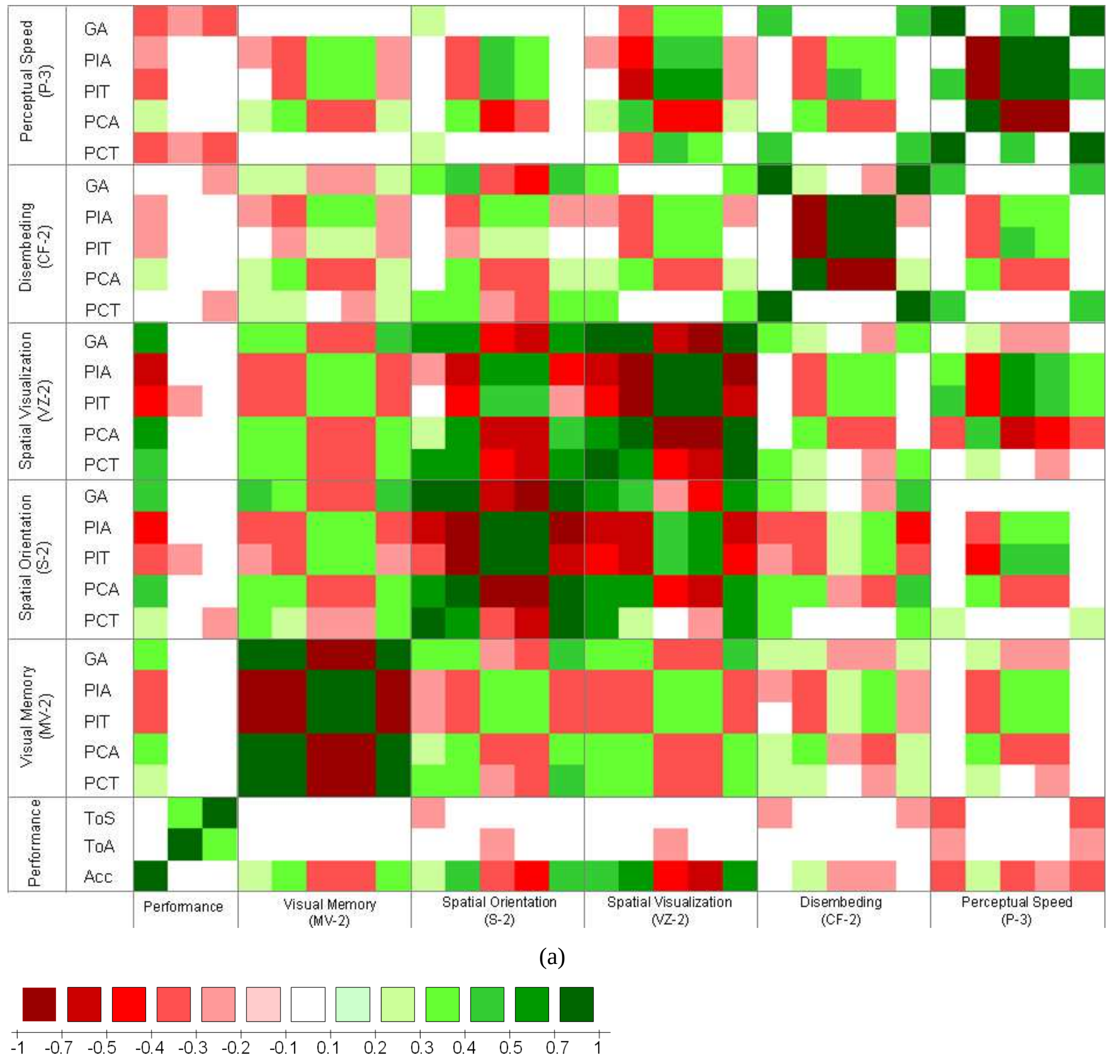


Figure 6.4: Projection analysis time, answer selection time, and difficulty of the object repeated in different rotations

be observed within the five scores of each cognitive test. Significant correlations were also found between tests. The strongest correlations can be seen between the scores of the spatial visualization test and spatial orientation test.

Figure 6.6 shows only the part of the correlation map that correspond to the correlations within the measures of performance and between performance measures and scores of cognitive factors tests. No significant correlation between accuracy and the two time measures was found and a positive correlation between Time of Analysis (ToA) and Time of Selection (ToS) was found.

Accuracy was found to be correlated to all tests of cognitive factors for almost all of the scores. Accuracy is highly correlated to the scores of the tests of Spatial Rotations (S-2) and Spatial Visualization (VZ-2). In these two tests, accuracy is positively correlated to the percentage of correct answers in all the test questions and in all the answered questions (PCT and PCA), and to the Guess Adjusted (GA) score. The negative correlations are found for the percentage of incorrect answers in all test questions and all answered questions (PIT and PIA) scores. In the case of the Visual Memory test (MV-2) scores, the absolute value of the correlations is lower when compared to the S-2 and VZ-2 tests, but the sign of the correlations



(a)

(b)

Figure 6.5: Correlation map between performance measures and the scores for the five tests of cognitive factors

remains unchanged. The PCA score in the Dissembeding test (CF-2) was the only score positively correlated to accuracy. PIT and PIA scores were negatively correlated to accuracy as well. The absolute value of the correlations between CS-2 scores and accuracy were low when compared to correlations found in CF-2, S-2 and VZ-2 tests. Most of the signs were inverted in the correlations between accuracy and the scores of the Perceptual Speed (P-3) test. All scores in the P-3 test were correlated to accuracy, and the only positive correlation is found with the PIT score.

It was also found that Time of Analysis, ToA, is inversely correlated with the PIT scores

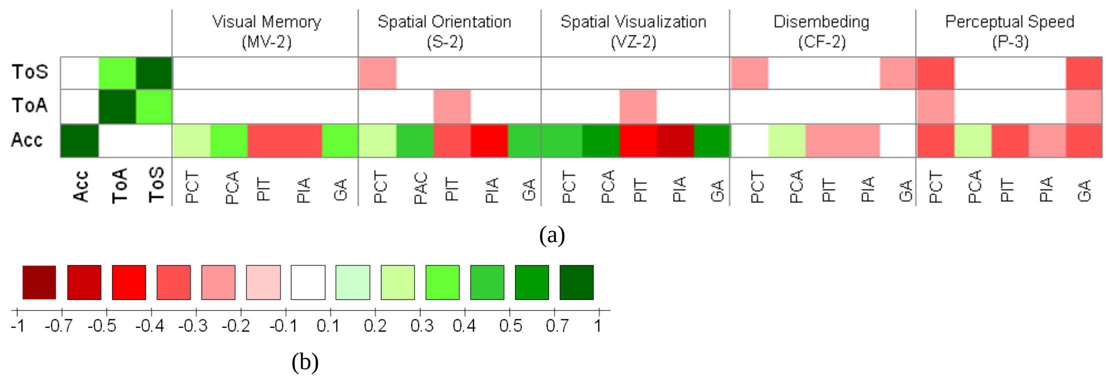
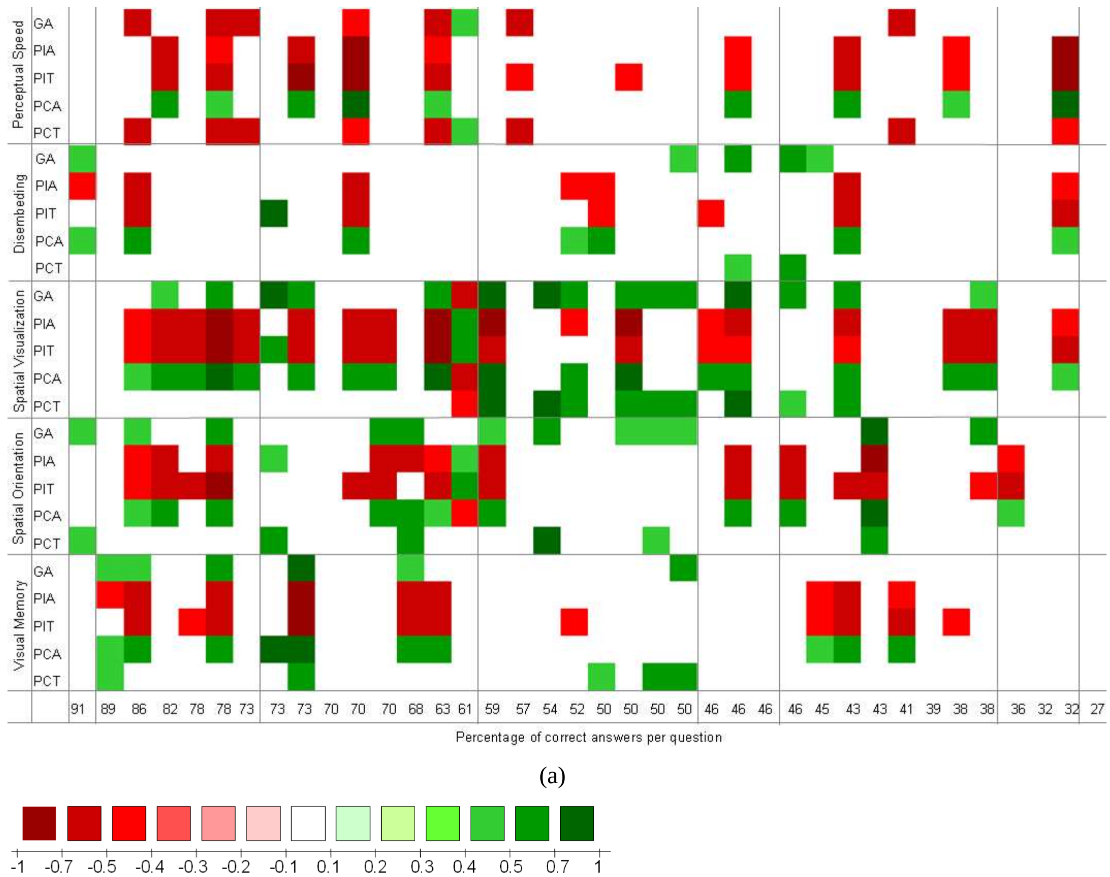


Figure 6.6: Correlation map between performance measures and the scores for the five tests of cognitive factors.

of the VZ-2 and CF-2 tests. Negative correlations were also found between ToA and the PCT and GA cores in the P-3 test. All correlations between ToA and the cognitive factors tests were relatively low. However, this correlation is small. Finally, the time participants took to select an answer is inversely correlated with Disembedding (CF-2) and Perceptual Speed (P-3), but the correlations are small. We are aware of the error growth generated by the t-tests analysis of gender differences, given that time to select an answer and accuracy are correlated. However, we are primarily interested in demonstrating the expected gender differences, so this problem does not impact our results.

A detailed correlation analysis between the cognitive ability tests scores and the accuracy of participants *in each question* found that the correlation between tests scores and accuracy change for visualization question. The correlation map in Figure 6.7(a) shows significant correlations at 0.05 levels. As seen on the color scale, white areas represent no significant correlations, green shades represent prositive correlations and red shades negative correlations. A histogram of frequency was created to represent the distribution of the answers of participants with high and low scores for each factor of spatial ability. The spatial skill level classification was based on the result of the Guess adjusted scoring method.

Accuracy was found to be correlated to at least one of the scores of the Shape Memory Test (MV-1) in 16 visualization questions. Five of the questions had significant differences in the distribution of the answer between low and high levels of Visual Memory. The overall accuracy in these 5 questions ranged from 38% to 89%, where participants with low scores were always negatively affected. It was observed that all the questions in this subset presented false answers



(a)

(b)

Figure 6.7: Correlation map between scores in the tests of spatial ability and accuracy for every question in the test. Columns represent visualization questions in decreasing order based on percentage of correct answers given by participants and horizontal blocks represent the five scores computed for each test of cognitive ability.

that corresponded to mirror images of the true orientation as shown in Figure 6.8.(a), or large rotations (90 or 45 degrees) away from the correct orientation in one axis only. It was also found that the distribution of answers from the high skilled participants clearly showed peaks (e.g., highest frequency) at the correct answer, while the answers of the low skilled participants were more homogonously distributed across all answers. The differences in the distributions can be seen in Figure 6.8 (b).

Spatial Orientation is one of the factors of spatial ability with highest overall correlation to the participants' accuracy in this study. 23 questions were correlated to at least one of the scores from the Cube Rotation Test. The correlations to accuracy can be classified as positive correlations to scores based on correct answers, and negative correlations to scores based on

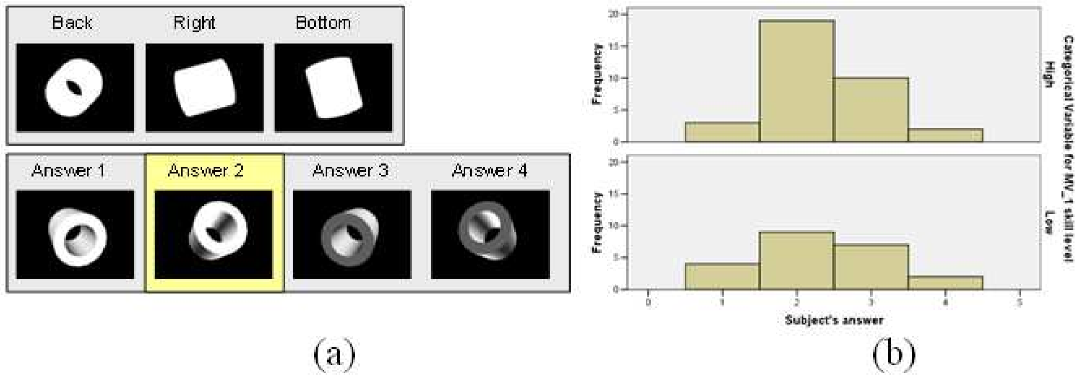
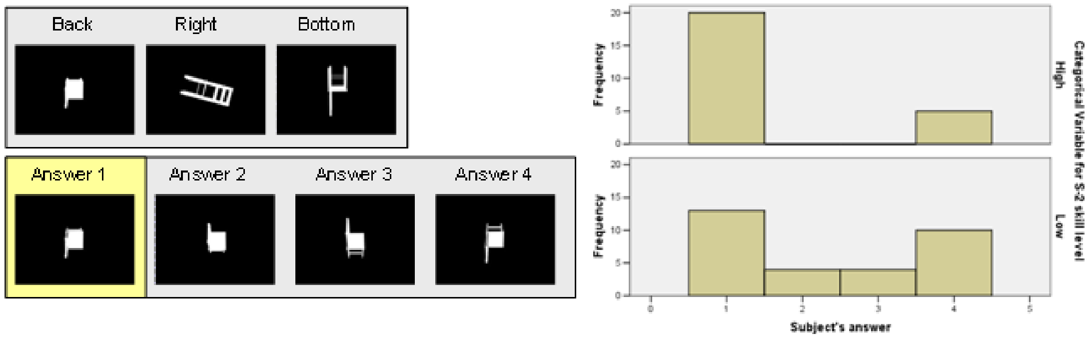


Figure 6.8: Visualization question where accuracy is correlated to scores in the Shape Memory Test. Image (a) shows the projections of a tube and the set of answer objects. The frequency histograms of the answers (b) from the low and high level participants show a more homogeneous distribution of answers in low level participants. The percentage of accurate answers in this question was 50%

incorrect answers. In the set of 13 questions with positive correlations, 5 showed differences in the distribution of answers from high and low level participants. All five cases had one false answer with rotated 15 or 30 degrees away from the correct answer. As illustrated by the question shown in Figure 6.9(b), all the distributions of answers by the high level participants peaked at the correct answer, while low level participants selected the false answer object with the smallest rotation and the correct answer with equal frequency. We found 10 questions with negative correlations between accuracy and the incorrect answers in the Cube Rotation Test. From those questions only two had differences in the distribution of answers between high and low level participants. No common characteristics were found in the answer objects or the distribution of answers in both questions.

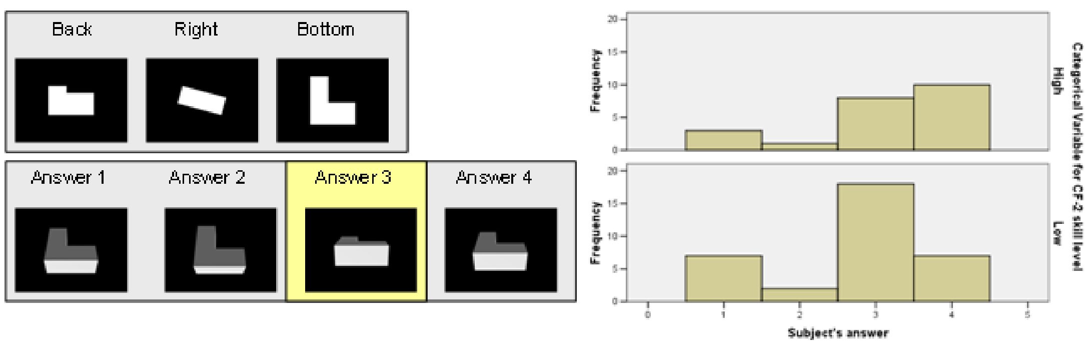
The Flexibility of Closure factor was correlated to accuracy in 11 questions. Five of these questions had different distributions of answers across high and low levels. In two questions high level participants were more accurate, but there were no common properties of the projected object or the false answers used. In the other three questions, low level participants were more accurate and selected the correct answer with more frequency that any other question, while high level participants selected the correct answer with the same frequency and any false answer within a 15 degree rotation as can be seen in Figure 6.10.

Accuracy in 14 visualization questions was found to be correlated to the Perceptual Speed



(a) (b)

Figure 6.9: Visualization question were accuracy is correlated to scores in the Cube Rotation Test. The false answer object (a) orientations are 15 degree apart. As seen in the frequency histogram of answers, high level participants were capable of distinguish between very close rotation angles.



(a) (b)

Figure 6.10: Visualization question where accuracy is correlated to scores in the Hidden Figures Test. The false answer object (a) orientations are 15 degree apart. As seen in the frequency histogram of answers, low level participants were capable of distinguish between very close rotation angles.

factor (evaluated with the Identical Figures Test P-3). We saw significantly different distribution of answers in five questions, where participants with high scores selected incorrect answers more frequently. Figure 6.11 shows the images and distribution of answers in one of the visualization questions.

Spatial visualization is the spatial factor with the highest number of correlations among all visualization questions. From the 24 questions correlated to scores in the Cube Rotation

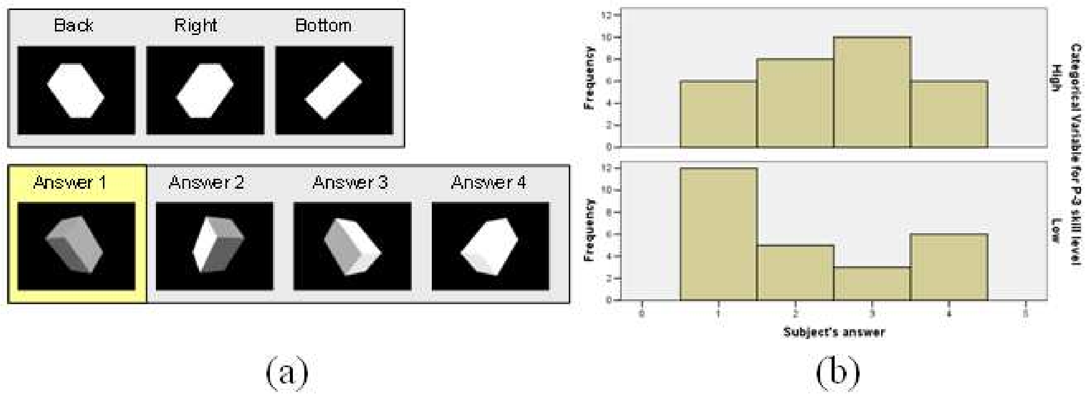


Figure 6.11: Distribution of answers for participants with high and low scores in the P-3 test. Participant with high perceptual speed were negatively impacted in the accuracy of their answers.

Test, 16 displayed differences in the distribution of answers: 5 questions presented false answer objects within 15 or 30 degrees of rotation from the correct orientation, and 11 questions presented mirror orientations. The highest correlations at 0.01 level were found in questions that used geon-based structures and real objects. High level participants were always found to select the correct answer with more frequency.

6.7 Discussion of Results

In order to determine how spatial abilities are related to the comprehension of projections, spatial abilities were defined as the skills measured by five tests from the Kit of Factor-Referenced Cognitive Tests. It was found that a high correlation between the spatial skill measures and two of the performance measures in the Projection Visualization Test, e.g., accuracy and time to analyze the projection. Studies of spatial skills have shown that the two spatial factors correlated with accuracy and consistently show gender differences in favor of males. Therefore, it was not surprising to find that there were significant gender differences in accuracy for the Projection Visualization Test that favored males.

Furthermore, time to analyze the projections was found not to be a factor influencing the accuracy in the Projection Visualization Test, but an individual difference, i.e., people who are accurate in this Projection Visualization Test were not always quick. Thus, using time as a dependent measure may mean that a visualization is being evaluated on how quickly it is perceived but not necessarily on how accurately it is comprehended. This may also affect the use of animation in visualization, which may be too quick for some participants to accurately comprehend it.

6.8 Chapter Summary

The fundamental research question to be answered in the first step of this approach is whether visualization comprehension skills related to other cognitive skills such as spatial ability. This chapter presents the results of the first experiment which measured visualization skills and analyzed their relationship to visualization without focusing on particular visualizations but on a “fundamental” task. The experiment presented in this chapter is designed to understand what visualization comprehension entails with regards to orthogonal projections. In this approach, individuals’ ability to comprehend the visualization and their spatial ability are measured and then analyzed in order to determine if they are correlated. Not surprisingly, it was found that spatial abilities are related to 3D visualization comprehension. In particular, spatial visualization and spatial rotation exhibited the strongest correlations. It was also found that problem solution time was not found to be related to visualization accuracy. Using these results, we can uncover what makes a difficult visualization based on the characteristics of the objects and their geometric properties. Table 6.5 presents a summary of the hypothesis and results found in Step 1.

Table 6.5: Summary of results from Study 1 based on initial hypothesis.

	Hypothesis or Questions	Confirmed?
H3	There will be a significant positive correlation between scores on the Shape Memory Test and Projection Visualization Accuracy	Yes
H4	There will be a significant positive correlation between scores on the Shape Memory Test and Projection Visualization Time of Analysis	No
H5	There will be a significant positive correlation between scores on the Cube Rotation Test and Projection Visualization Accuracy	Yes
H6	There will be a significant positive correlation between scores on the Cube Rotation Test and Projection Visualization Time of Analysis	No
H7	There will be a significant positive correlation between scores on the Paper Folding Test and Projection Visualization Accuracy	No
H8	There will be a significant positive correlation between scores on the Paper Folding Test and Projection Visualization Time of Analysis	No
H9	There will be a significant positive correlation between scores on the Identical Figures Test and Projection Visualization Time of Analysis	No
H10	There will be a significant positive correlation between scores on the Hidden Patterns Test and Projection Visualization Accuracy	Yes
H11	There will be a significant positive correlation between scores on the Hidden Patterns Test and Projection Visualization Time of Analysis	No
H12	Correlations of the Paper Folding Test Scores with Visualization Accuracy will be significantly higher than Correlations of the Shape Memory Test Scores with Visualization Accuracy	Yes
H13	Correlations of the Paper Folding Test Scores with Visualization Comprehension Time will be significantly higher then Correlations of the Shape Memory Test Scores with Visualization Time of Analysis	Yes
H14	Correlations of the Cube Rotation Test Scores with Visualization Accuracy will be significantly higher then Correlations of the Shape Memory Test Scores with Visualization Accuracy	Yes
H15	Correlations of the Cube Rotation Test Scores with Visualization Comprehension Time will be significantly higher then Correlations of the Shape Memory Test Scores with Visualization Comprehension Time on Analysis	Yes
H1a	Males will be significantly more accurate than females in the Projection Visualization Test	No
H1b	Males will have significantly higher scores than females in the Cube Rotation Test	No
H1c	Males will have significantly higher scores than females in the Paper-Folding Test	No
H2	Females will have significantly higher scores than males in the Shape Memory Test	No

Chapter 7

Step 2 - Visualization Comprehension, Visual Properties and Strategies

7.1 Introduction

As shown in Chapter 6, individuals' scores in certain tests of spatial ability were correlated to their ability in visualization comprehension. Participants with the lowest scores in some of the tests were found to be less accurate in the visualization test. This information is used in the second step of the methodology for the generation of knowledge regarding visualization difficulty in this dissertation.

This chapter describes the analysis and studies aimed at identifying visual properties that make the visualization questions difficult to comprehend. First, results from the correlation between spatial ability skill and visualization comprehension were used to guide an exploratory analysis to identify geometric properties that make visualizations difficult to comprehend. In this analysis spatial abilities were used to isolated questions from the visualization test that only a group of participants with the same level of spatial ability skill found difficult or easy to comprehend. Those sets of visualization questions were compared statistically in order to identify geometric and visual properties that were significantly similar among those visualization questions.

In addition to the exploratory analysis of the results from Study 1, this chapter presents the results from the load protocol experiment conducted in Study 2. In this load protocol analysis, participants were asked describe their thought processes as they analyze and answer each visualization question on the visualization test. Participants' descriptions of strategies were analyzed and relevant visual properties were identified.

7.2 Exploratory Analysis of Study 1[1]

As described on Chapter 6, some of the questions are clearly more difficult for participants classified in different levels of spatial ability. In order to identify the properties that determine test difficulty, it is necessary to quantify the characteristics of the visualization and the 3D objects represented on the visualization questions. The geons used in Study 1 can be defined in terms of their 2D view-independent properties as defined by Biederman [10] (i.e., collinearity of points or lines, curvilinearity of points, skew symmetry, parallel curves over small visual angles and vertices).

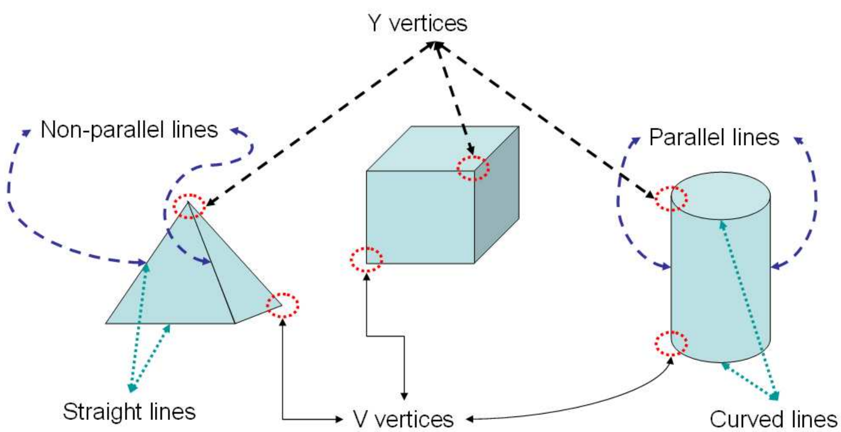


Figure 7.1: Example of view-dependent properties in geons

According to Geon theory, these 2D properties are used by the perceptual system to determine the shape of 3D objects. Since the projection visualization represents 3D shapes by means of 2D projections with solid shading, some of the 2D properties change. For instance, the center object in Figure 7.1 can be clearly identified as a cube, and the 2D properties that define it are clearly visible. A flat-shaded front projection of the same object makes the shape more difficult to identify because some of the 2D properties are missing or they have changed. In some cases, the object cannot be reconstructed unless three 2D projections are provided because no one projection contains all the information needed. Higher cognitive and problem solving skills are required to integrate the information from all projections to reconstruct the

[1]Parts of this section were published on the paper: Maria Velez, Deborah Silver, Marilyn Tremaine. Understanding Visualization through Spatial Ability Differences. Proceedings of Visualization 2005. IEEE, pages 511-518. Minneapolis, Min. 23-28 Oct, 2005.

object shape.

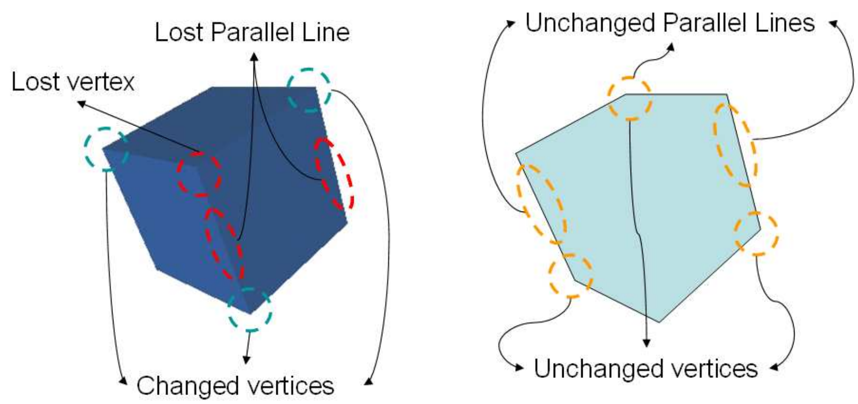


Figure 7.2: Example of view-dependent properties that are lost or changed when the 3D object is presented as a 2D projection.

This analysis constitutes an exploratory study of the visual and geometric properties that define the 3D objects and their projections. The following properties were quantified for each visualization question:

1. Number of surfaces, edges and vertices in the original 3D object.

2. Number of distinct surfaces, edges and vertices projected in the three orthogonal projections, i.e., number of the surfaces, edges and vertices that would be visible in a wire frame rendering of the projection.

3. Number of visible surfaces, edges and vertices in the three orthogonal projections, i.e., number of visible surfaces, edges and vertices in a uniformly shaded object.

4. Differences in orientation between the object and the three incorrect answers.

5. Realistic vs. geometric objects.

An example of the quantification of properties a)visible in the 3D object, b)visible in a wire-frame projection and c) visible in a solid projection are shown in Figure 7.3. For each geometrical object, the ratios between properties shown on 7.3. b and 7.3.c for each projection were calculated. Then, the median of the three ratios was selected as the characteristic ratio for the question. In the analysis, the ratios and properties are correlated with the participants' performance measures in the visualization test.

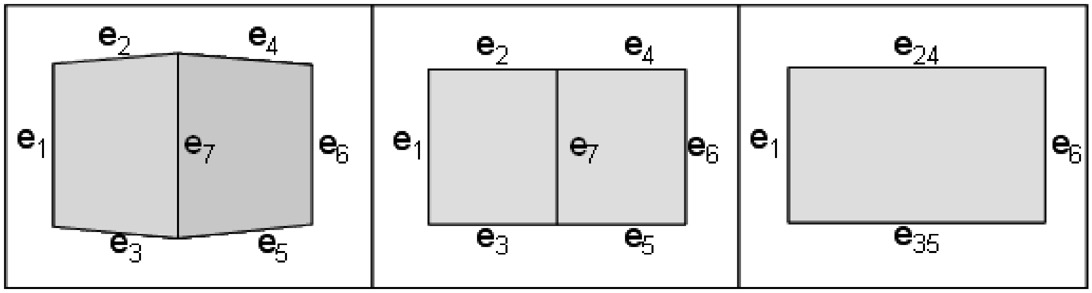


Figure 7.3: Quantification of visible and distinct edges in a cube. Figure 3-a shows the edges of a 3D cube seen from one point of view. Figure 3-b illustrates how these edges are mapped to an orthogonal representation. In this case we identify seven distinct edges. Figure 3-c shows the solid projection of the cube. Edge e7 is not visible, and edges (e2, e4) and (e3, e6) are merged. There are four distinct edges in this projection

7.2.1 Results

Four geometric and visual properties were quantified for each question in the visualization test: total, distinct, and visible surfaces, edges and vertices; and angle differences between 3D answers. Another set of properties computed was the median ratio between distinct and visible surfaces, edges and vertices for the three projections (i.e., back, bottom and right). These median rotations were used to build the average median ratio for each question.

Table 7.1 shows the results of a one-tailed Pearson correlation analysis between the spatial skill measures, property counts and the average median of ratios. It was found that the time participants spent analyzing the projections was significantly correlated with all properties and ratios. However, properties and ratios were not significantly correlated with the time to select an answer. It was believed that correlations indicate that the time it takes to create a "mental image" of an object is highly correlated with the complexity of the object which is quantified by the property counts. It also indicates that time is correlated with the number of details lost in the projection as is quantified by the property ratios. It was found that the time to select an answer was not affected. Accuracy was only correlated with the ratio between the visualized and distinct surfaces, but not with the property counts. This result suggests that the complexity of the original object does not make it more difficult for the participant to reconstruct mentally, but rather those elements that had to be interpreted or integrated. Accuracy was found to be correlated with all the ratios between visualized and distinct surfaces, but not with the property counts. This result supports the goals of viewpoint entropy [84]. In viewpoint entropy, a good viewpoint is one that contains a high level of information about an object. Here, it is shown that the viewpoint is a factor that has a direct effect on the formation of the mental image even for simple objects.

As pointed out in Section 6.3.1, realistic objects were used in Study 1. Those objects replicate the orientations used by other geometric objects, so as to detect any significant differences in performance due to the realistic or abstract nature of the objects. A t-test analysis failed to find any significant differences in accuracy ($t = 1.232$; $df = 18$; $p < .235$), and time of analysis ($t = 0.70$; $df = 18$; $p < .945$) for realistic and geometric objects. An analysis of brain activity, studies has found that realistic objects are processed in a different way than novel or abstract objects. It was expected that familiarity with the shape of an object would make it easier for the participants to recognize the objects in our visualization thereby facilitating the creation of an accurate “mental picture” of the 3D object. However, this result contradicts these expectations although several experiment participants commented that it was easier to create a “mental image” for realistic objects. Further study of these effects will be needed in order to sort out the results regarding realistic objects.

Given that it was found that accuracy in the visualization test was significantly and highly correlated with the scores on the Spatial Orientation test and Spatial Visualization test (see Figure 6.6 in Chapter 6), the next step is to identify which of the question properties may cause accuracy differences among participants with different levels of spatial ability. The purpose in this exploration was to find out which properties of the visualization are causing visualization comprehension problems.

The first direct approach was to compare the properties of all the correctly answered questions with those that were incorrectly answered. This analysis found no significant differences for any of the properties we identified. Given that it is known that a large amount of visualization comprehension is accounted for by individual spatial ability, the scores on the spatial ability test were used to examine the properties in more detail.

Table 7.1 shows the results of a Pearson correlation analysis between performance in the visualization test and property counts of the objects used in the visualization questions: r = Pearson value; p = probability level of significance.

Table 7.1: Pearson correlation analysis between performance in the visualization test and property counts of the visualized object: r = Pearson value; p = probability level of significance

Property counts and ratios			ToA	ToS	Acc
Count	3D Object Surfaces	r	.453[2]	-.061	-.101
		p	.008	.379	.305
	3D Object Edges	r	.376[1]	-.069	.002
		p	.024	.363	.496
	3D Object Vertices	r	.371[1]	-.081	.024
		p	.026	.341	.452
Median of Ratios	Visualized / Distinct Surfaces	r	-.638[2]	.130	.424[1]
		p	.026	.341	.012
	Visualized / Distinct Edges	r	-.512[2]	-.206	.536[2]
		p	.003	.147	.002
	Visualized / Distinct Vertices	r	-.531[2]	-.241	.425[1]
		p	.002	.108	.012
Sum of rotation difference		r	.110	.148	.409[2]
		p	.289	.227	.015

[1] 1-tailed significance at $p < .05$ N = 28; [2] 1-tailed significance at $p < .01$ N = 28.

First, subjects were divided into two groups, high spatial ability (HS) and low spatial ability (LS). This was done based upon their score on the Paper Folding test. Then, the set of questions that only the HS participants got correct were isolated. This set was compared to the entire set of questions to see if there was a significant difference in any of the geometric properties. The total number of edges ($t = 1.942$; $df = 12$; $p < .029$ 1-tailed) and the total number of vertices ($t = 2.009$; $df = 26$; $p < .028$ 1-tailed) were found to be significantly higher in the questions where high spatially skilled users were more accurate. It was found that the ratio of visualized and distinct surfaces ($t = 1.782$; $df = 25$; $p < .044$ 1-tailed) in this set of questions was significantly lower. Then, the analysis proceeded to find out which properties made the visualizations so difficult that even HS participants could not answer the questions. The set of questions that the HS participants answered incorrectly (6) were compared to the overall set of questions. No significant differences were found. However, the sample size may have been too small to conduct this kind of detailed analysis.

7.2.2 Discussion of Results

It can concluded from the analysis of object properties that high spatially skilled participants can create accurate mental images of objects that are significantly more complex than those of participants with lower spatial skills. High spatially skilled participants are also better at comprehending projections with a higher number of “hidden” surfaces.

With regards to visualization difficulty, an overall evaluation of the geometric properties of the object, and the “hidden” properties in the visualization of the object showed that the complexity of the 3D object affects both accuracy and time needed to create a mental picture of the object. Both the ratio of hidden properties in the visualization and the property counts were affecting participants’ accuracy. It was also found that high spatially skilled participants can comprehend the projections better than others when complex objects and incomplete visualizations are provided. These findings may have ramifications for the design and accessibility of visualization techniques expected to be used by the general public.

7.3 Study 2 Design

A verbal protocol is often used in cognitive problem solving tasks to gain an understanding of how humans go about solving problems they do not quite understand [28]. Although think-aloud reports fall short from instantly revealing the underlying cognitive processes that take place while participants answer each visualization question, we can use them to infer how participants integrate the images presented by the three projections, which visual information is incorporated into their thinking process, what assumptions they make and what factors lead to the selection of incorrect answers. This section presents the results from a protocol analysis conducted on a small set of subjects ranking as low, medium and high levels of spatial skill based on their scores in the Paper Folding Test (VZ-2).

7.3.1 Task

This study used the mosaic display of projections used on Study 1, as well as new visualization questions using in-place projection display. Sequential presentation of the answers was used in this study. Three of the five participants in study 2 analyzed visualization questions in the mosaic format, and the other participants were given visualization questions with the in-place format.

The visualization test lasted one hour and participants were asked to solve as many visualization questions as possible. Between 38 and 56 visualization questions were used.

7.3.2 Stimuli

Visualization test using mosaic format used the visualization questions used on study 1. These visualization questions used new real and geometric objects that were later used on Study 3.

7.3.3 Participants

Five participants were recruited from the student population at Rutgers University, New Jersey campus. All subjects received an USB drive for one hour of participation. Participants were ranked as low, medium and high level of spatial skilled based in their scores based on their scores in the Paper Folding Test (VZ-2) and the Cube Comparison Test (S-2) according to the parameters of classification used on Study 1. The two female participants that ranked as low spatial are undergraduate students in psychology and neuroscience. Two participants ranked as medium level of spatial skill are students enrolled in the undergraduate and graduate physics program, and the participant ranked as high level of spatial skill is a male graduate student in electrical and computer engineering.

7.4 Method

Participants are asked to create a mental picture of the 3D object represented by the 2D projections while describing verbally their thought process. They are also asked to explain the rational behind the selection of the answers. Time participants take to analyze the projections and select answers is increased because they are asked to verbally describe their thought process, it will not be considered as a measure of performance.

7.4.1 Procedure

Participants were taken to an office where only one experimenter was present. After given written consent, they took the Paper Folding Test (VZ-2) and the Cube Comparison Test (S-2). Then, the computer-based visualization test was administered. Subjects were placed in front of desktop computers on which the visualization test was displayed. Subjects were given an introduction to the visualization test, and they were had the opportunity to ask questions followed by five practice questions. Participants were asked to answer as many visualization questions as possible in 60 minutes.

Participants were asked to think aloud while analyzing the visualization questions and their voice and actions in the screen were videotaped. In particular, the experimenter asked the subjects to verbalize their thoughts, to describe what they were looking for in the images projections, to state what relations they were forming, if any, and to describe the final mental image they formed of the projected object before moving to the answer selection screen.

7.5 Expected Results

Studies of individual differences in various spatial tasks have found that many different strategies can be applied to solve spatial problems. In fact, individuals can apply different type of strategies, selecting the most appropriate strategy based on the difficulty of the visual-spatial problem. Strategies can be classified in a continuous spectrum of *Holistic* to *Analytic* strategies [36]. Holistic strategies are characterized by the use of spatial representations of the problem. The mental representation in holistic strategies is based on spatial properties and their relations. Analytic strategies reduce the problem to a series of non-spatial properties and relations between patterns. Analytic strategies are believed to be preferred in the solution of difficult spatial problems.

It is anticipated that participants will use holistic and analytic strategies. Also, *it can be expected that participants with lower spatial skill (as measured by the Paper Folding Test and the Cube Comparison Test) will rely on holistic strategies to analyze the visualization questions*.

Based on the description of holistic and analytic strategies observed in other spatial tasks, it is reasonable to expect the following characteristics in holistic and analytic strategies for the visualization test:

Participants using holistic strategies will:

- 3D object is described as a list of properties instead of forming a “mental image”
- Rely on pattern matching between projection shapes and the outline of 3D objects in the

Table 7.2: Summary of participants' spatial skill and characteristics of the visualization test

Participant	SA skill level	Layout	Questions answered
Participant A	Low	Mosaic	34
Participant B	Low	In-place	46
Participant C	Medium	Mosaic	38
Participant D	High	Mosaic	36
Participant E	High	In-place	40

answer screen

- Relations between projections are not established

Participants using analytic strategies will:

- Describe the unseen 3D object in 3-Dimensional terms instead of 2D shapes.
- Describe the orientation of the object in 3-Dimensions.
- Analyze how the shape and orientation of the unseen 3D object affect shape, scale and orientation in all 2D projections

7.6 Results

Participants' transcripts were analyzed looking for clues of the properties and processes used by participants to reach a solution. The references to shapes, spatial position, orientation, relative size, spatial relation, matching of patterns and any other objects and space were marked for all participants and for each visualization question. This information is used to describe the general strategies exhibit by the five participants in this experiment,

Participants will be referred to as *Participant A* to *Participant E*. Table 7.2 presents the participants' level of spatial skill, the visualization question layout used, and the number of visualization questions answered.

7.6.1 Candidate Problem Solving Strategies

Based on the information yieled by the analysis of the verbal protocols collected in this study, the following strategies are proposed as strategies to reconstruct a 3D object based on three 2D orthogonal flat-shaded projections.

Table 7.3: Comments from Participant B during analysis question 2. Projections and the selected answer are shown.

	*"I am not exactly sure how to visualize it"* [referring to projections]*"but... I would imagine... I actually don't know but... I'm just going to go over to the next screen to see the questions related to the object now, I am going to try to remember what I see here, two rectangles and..."* [click to go to next screen]
	*"To be honest, I do not know why number 1"* [3D object] *"and number 4. Once again A does not have a strategy for this selection, but for some reason number 1 looks right and number 4 looks like it may be possible... I will choose number 1..."*

Pattern matching strategy

This strategy is highly specialized to fit the format of the visualization test. Participants first memorize one or more of the shapes displayed in the projections. Participants in Study 2 preferred to memorize the back and right projections regardless of the shape displayed in them. Participants used 2D shapes to describe the projections, such as square, box, circle and pentagon. They also focused their attention on scale differences between projection shapes and whether the shape was tilted. To select an answer, participants compared the memorized shapes with the outline of the 3D objects in the set of possible answers. Table 7.3 presents excerpts from Participant B's transcript regarding the solution of question number 2 in the experiment session. Participant B expresses that memorization will be the strategy used and selects the answer object that best fits the images in the projection. In this case, the participant uses the bottom projection. Orientation information is not mentioned in the description of the shape not in the selection of the answer.

This is the simplest strategy possible as it does not require any type of mental structural reconstruction. Due to the simplicity of the information used to describe the 3D object the following kind of mistakes were made in the selection of the answers:

- Objects in mirror orientations were selected because they must have one projection that is identical projection

- Objects in mirror orientations were selected because the participants did not encode the orientation of the shape in the projection

- Objects with 45 degree rotations are often selected as the correct answer because detailed information regarding angle of rotation of the shape was not encoded by the subject. The 45 degree angle was usually selected because it was perceived by participants as not to tilted.

- Guessing occurred then participants could not find an object that match the shape they were looking for. They tend to select an object that resembles the shape they remember even if they know the orientation is not correct.

During the course of the experiment session, participants A and B made improvements to this strategy:

- Detailed information about orientation and angle of rotation was made part of the object description.

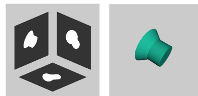
- Participants started to recognize 3D objects that can create some of the projections (although no mention of 3D characteristics are made)

Property-based description strategy

High spatial participants showed a tendency to prefer holistic strategies to solve all the visualization questions. However, Participant E presented an alternative analytic strategy in which lists salient 3D properties of the objects without recreating its 3D structure. The description of the object included degree of rotation around the x, y and z axes, location of edges relative to the object, curved vs. straight object axis, and object surfaces.

Although the participant named a comprehensive list of visual properties, some of the properties values were forgotten by the time of the answer selection. Since only one participant used this strategy, only one type of error was observed: Objects in mirror orientations were selected because the participant forgot the value of the general orientation of the object. Forgetting any of the properties listed in the description of the object may lead to an incomplete or incorrect representation.

Table 7.4: Comments from Participant B during analysis of question 15. Projections and the answer selected are shown.

	*"For this image... I mean the image I just clicked on"* [referring to projection] *"I assumed that there was going to be a circle, an oval circle over here... so in other words this circular part here of the picture will appear on the left instead of the right... and this image is facing the right so I am going to eliminate it. This picture is facing left and back. That is what I was looking for"* [referring to 3D objects]

Shape-based feature matching strategy

Shape-based feature matching strategy is still mostly analytic, but it has some characteristics attributed to holistic analysis. This strategy uses the 2D shapes displayed in the orthogonal projections and matched the shape to surfaces or faces of the 3D object. Participants described the unseen 3D object as an object having a surface in a particular area of the 3D object that corresponds to the shape of the projection. Participants applied this strategy most effectively if projections showed a simple shape such as a box, circle and triangle. Properties of the 2D surfaces such as scale, relative size and detailed rotation were better encoded than in they were in the pattern matching strategy.

Table 7.4 describes an example of mapping properties of the 2D projections, in this case orientation and a circular surface to the shape of the answer objects.

This strategy does not lead to a full mental reconstruction of the 3D object, but it incorporates spatial information in the mental description. Participants in Study 2 seemed apply this strategy selectively, switching usually to a pattern matching strategy when the shape projections was not simple enough. Common errors observed on by participants using this strategy are:

- Objects in mirror orientations were selected because they must have at least one identical projection

- Guessing occurred then participants could not find surfaces that match the shape they were looking for. They were usually not able to see how more than one surface can create to select an object that resembles the shape they remember even if they know the orientation is not correct.

During the course of the experiment session, participants A and B made improvements to this strategy:

- Integrated information from a second projection to determine the orientation and location (relative to the whole object) of that surface.

Shape extrusion strategy

This strategy can be defined by two steps. Participants (1) select the shape that gives "the most information". That is, select a projection that provides unique information (when compared to the others) such as shape and 2D orientation (e.g., square, tilted box, triangle pointing up, etc.) Then, they (2) extract information about the orientation of the 3D object. Participants used shape description on step (1), and extrude it using the axis defined by the information gathered on step (2).

This strategy was usually applied to objects aligned with two of the main planes (i.e., x-y, y-z and x-z plane). However, for objects with a curved axis (e.g., arches) or objects rotated around two or more axes, this may lead to inaccurate representations of the 3D objects. Mistakes made in the selection of the answers after using this strategy include:

- Objects with different degrees of rotation in the same octant are mistakenly selected as the correct answer because specific degrees of rotation is not recalled by participants.
- Objects shape description was incorrect because participants extruded the 2D shape using axis orientation information.

After several visualization questions were answer, paticipants improved this strategy by:

- Recognizing that size of the shapes in some projections is affected by rotation in one axis because more than one object surfaces are projected

- Learning to identify the shape of the “cross section” in objects with a curved axis, such as arches

Incremental structure refinement strategy

Incremental structure refinement strategy strategy was used by participants with medium or high level of spatial skill, but only participants D and E were able to successfully apply this holistic strategy to all visualization questions regardless of difficulty.

The incremental structure refinement strategy starts like the Shape extrusion strategy. A 2D shape in one of the projections is selected as a cross-section, and extruded using orientation information extracted from other projection. Participants then check of their mental representation fits all the projections. If that is not the case, the projections are analyzed and new information is added to the mental representation. The properties participants look for on the projections are the same properties identified in the property-based description strategy. However, instead of creating a list of identifiable features, participants integrate the information to a 3D mental model. After every update of the mental representation, participants check if the 3D object they have defined corresponds to the projections seen on the screen. Also, participants often identify features such as corners and edges that are visible in more than one projection.

The most common errors related to this strategy were related to the specific angle of rotation of the object, especially then there are rotations in more than one axis.

7.7 Chapter Summary

This chapter presented an exploratory analysis of the data collected in the first experiment analysis. The goal of this step on the approach proposed by this dissertation is to answer the question: What characteristics of the projection visualization make it difficult to comprehend?

The geometric properties of the visualization objects were computed, and “hidden” properties in the visualization of the object (e.g., non-visible corners, surfaces and edges) were found to create larger comprehension difficulties. The complexity of the 3D object affected both accuracy and the time needed to create a mental picture of the object and had a larger effect on those with low spatial abilities.The properties that were identified as difficult to comprehend are used to create a training method that gradually increases the difficulty of the questions in the visualization tests by introducing the properties one by one. Participants are given several test questions were the same property is presented. This training is expected to allow participants to be aware of the property and be able to mentally reconstruct different objects.

This chapter also presented the results from a protocol analysis that included five participants with various levels of spatial ability skill. The analysis uncovered five distinct strategies used by participants to solve the visualization task. As shown on Figure 7.4, strategies ranged from holistic to analytic in nature, and participants were found to use more than one strategy during the visualization test.

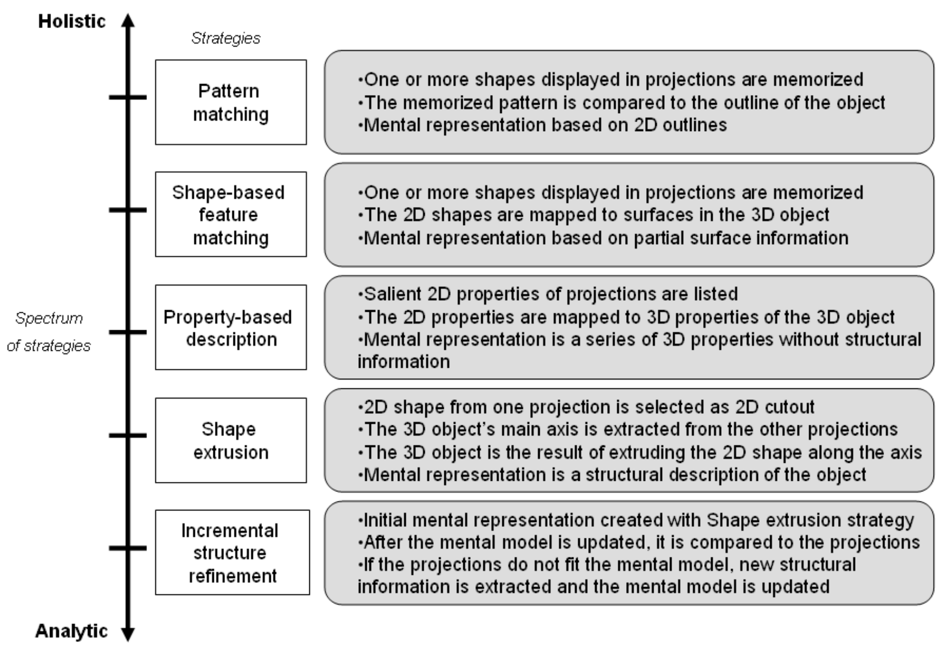


Figure 7.4: Continuum spectrum between holistic and analytic strategies and description of spatial strategies.

The next chapter describes Study 3 where basic training was given to experiment participants and discusses the improvements and limitations of using these properties to quantify visualization question difficulty, as well as the viability of training to improve viewers visualization comprehension skill.

Chapter 8

Step 3 - Effect of Incremental Training on Visualization Comprehension [1]

8.1 Introduction

Visualization designers facilitate the comprehension and analysis of the data by applying transformations such as filtering, summarization and mapping of relations to visual-spatial properties. Therefore, the effectiveness of visualizations partly depends on the visualizer's ability to comprehend the information conveyed by the artificial, and often abstract representations used by the visualization designers. The competences and strategies required from users to comprehend the mapping between data and visual representation are fundamental to the comprehension of visualizations. Contrary to the expectations of designers, the strategies used by viewers may result in incomplete or incorrect mental representations of the information that the visualization is expected to communicate. In fact, researchers argue that without formal training, comprehension of visualizations may not improve. In order to improve individual's visualization literacy, this dissertation advocates for the development of training methods aimed to develop and refine the analytic strategies that allow viewers to comprehend the mappings between data and visual properties used in visualizations.

The goal of the study described in this chapter is twofold. First, understanding and quantifying what makes a visualization difficult is a basic step towards the development of a theory of how individuals with diverse skills comprehend visualizations. If the training is successful, the properties used to determine difficulty of visualization questions have a higher likelihood to be related to difficulty in visualization comprehension. And second, since quantification of

[1] Parts of this chapter were published in the paper: Maria Velez. Visualization Diversity: A Cognitive-Based Training Method for Visualization Comprehension. IEEE Visualization/VAST Doctoral Colloquium at IEEE Visualization 2006 in Baltimore, MD, October 2006.

the difficulty is fundamental in most training methods, the results from the basic training presented in this chapter will also help the development of fully developed training programs for the general population.

This chapter describes the development and evaluation of a training method based on the controlled exposition of individuals to visualization questions with increasing level of difficulty. Difficulty of the visualization questions is determined based on the visual properties discussed in Chapter 7). An experiment was designed to determine if training individuals by introducing incrementally harder visualization question improves their visualization comprehension better than individuals who are not trained in this fashion. To test whether these properties predict visualization difficulty and if incremental training is viable or not, experiment participants were divided in two groups that were trained using the same materials presented in different order. In one case the visualization questions were be ordered by geometric properties with the simplest ones occurring first. In the second case, the visualization questions were randomized, that is, hard ones will follow simple ones and vice versa and no grouping of visualization questions were no grouped with a specific property. This will be referred to in short as ordered incremental training vs. unstructured training.

8.2 Pilot

8.2.1 Task and Stimuli

The visualization questions in this pilot followed the in-place layout and sequential presentation of answers shown on Figure 8.3.1. The visualization task asked from viewers was not changed compared to Study 1: participants were asked to analyze the projections and build a “mental picture” of the unseen 3D object they represent.

Four possible answers (3D objects in different orientations) were displayed sequentially, showing one of the four at a time on the screen. Participants were able to rotate the objects ± 90 deg around the vertical-axis. The objects used on the visualization questions include single geons and objects compounded by 2 or more geons as shown on Figure 8.3.

Table 8.1: Gender and field of study of participants of participants in the pilot for Study 3.

Participant ID	Gender	Field of study
VD01	Male	Political science
VD02	Female	English
VD03	Male	Political Science
VD04	Female	Animal science
VD05	Female	Pharmacy
VD06	Female	Business / Chemistry
VD07	Female	Not specified
VD08	Male	Finance
VD09	Male	Physics
VD10	Male	Biological Sciences
VD11	Male	Industrial Engineering
VD12	Female	Undecided

8.2.2 Participants, Experimental Setup and Procedure

Twelve participants (6 females and 6 males) were recruited from the graduate and undergraduate student population. Their average age was 21 years, ranging between 19 and 25 years. All participants received a $25 Knight Express Card when they completed all experiment sessions. Table 8.1 presents participants gender, field of study and level of study.

Participants were assigned randomly to one of two training treatments. The first treatment presented visualization questions ordered incremental training and unstructured training. Both training treatments are divided in four sessions and use the same visualization questions, but the order in which the questions are presented is different. The ordered incremental training presents visualization questions in increasing order of difficulty using the visual properties described in Chapter 7. The unstructured training present the visualization questions in a pre-assigned random order. Each session presented one or two sets of visualization questions that shared common properties:

- Session 1 presented 20 visualization questions with objects with rotation in one axis, and false answers with orientation differences of $\pm$45deg or more.
- Session 2 presented 40 visualization questions objects with rotation in two axis, and false answers with orientation differences of $\pm$45deg and $\pm$30deg.
- Session 3 presented 40 visualization questions objects with rotation in three axis, and false answers with orientation differences of $\pm$45deg and $\pm$30deg.

Table 8.2: Descriptive statistics of time of analysis (ToA) and accuracy (Acc) in the Visualization Test, and scores on spatial ability tests for the 12 participants in the pilot for Study 3.

		Visualization Test		Mental Rotation Test			Paper Folding Test		
		Acc(%)	ToA(sec)	Total	Correct	Incorrect	Total	Correct	Incorrect
Incremental	Mean	.61	21.95	27.33	14.83	12.50	11.50	8.33	3.16
	S.D	.48	17.51	10.25	5.70	6.71	2.25	2.25	2.78
	Max.			40.00	25.00	20.00	15.00	12.00	7.00
	Min.			16.00	10.00	3.00	9.00	6.00	0.00
Unstructured	Mean	.68	11.07	25.00	19.16	5.83	16.00	11.50	4.50
	S.D.	.46	8.38	7.09	5.15	4.62	3.22	3.27	4.32
	Max.			35.00	27.00	15.00	20.00	15.00	13.00
	Min.			15.00	12.00	3.00	12.00	6.00	2.00

- Session 4 presented visualization questions with rotation in one, two or three axis, and and false answers with orientation differences of $\pm 15deg$.

Before the visualization test was administered, participants read a detailed description of the experiment, answered a short questionnaire and took two test of cognitive ability: the Mental Rotation Test (M.R.T. Test) and the Paper folding Test (VZ-2 Test). Participants took both tests again after session 4 was over.

Performance on the visualization test was measured in terms of (1) the accuracy of the answers, and (2) the time to select an answer from the set of four answers (in seconds). Three scores were computed for the cognitive tests: number of correct answers, number of incorrect answers and total number of answers.

8.2.3 Results

Both variables of performance in the visualization test (Time of Analysis and Accuracy) were not normally distributed. Table 8.2 shows the descriptive statistics for Time of Analysis and Accuracy for the incremental and unstructured training. Overall, participants in the unstructured training had higher accuracy than participants on the incremental training. However, participants assigned to the unstructured training had higher scores in both test of cognitive abilities as seen on Table 8.2. Since the scores on the cognitive ability tests are positively correlated to accuracy in the Visualization Test, it is likely that the accuracy results in both training methods are the result of the disparity between initial groups instead of result from training.

Figure 8.1 shows the accuracy (percentage of correct answers) in each subset of questions for the Incremental and unstructured training groups. The Incremental training group shows a steady increase in accuracy for subsets 1 to 5 while the accuracy of participants on the unstructured training decreased.

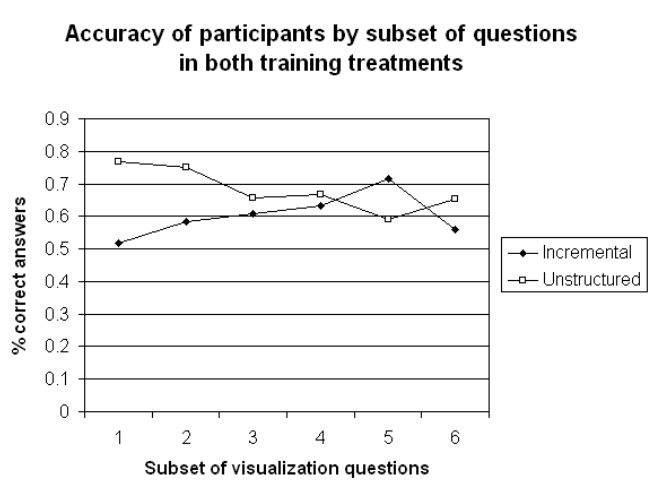


Figure 8.1: Accuracy of participants in the Incremental and Unstructured training in 6 subsets of questions of pilot study

8.2.4 Discussion of Results

Based on the observations made in this pilot study the following changes will be introduced on Study 3:

- Session 1 included the introduction to the visualization test with a series of "practice questions" that were not considered part of the visualization test. The introduction was followed by 20 visualization questions, so the accuracy and time results may reflect the training in how to use the software that participants received. To make all training sessions more uniform, the introduction to the software and the visualization test will be given in the first session and the actual visualization test will start on Session 2.

- One extra session of training will be added to the training treatments. This way, there is no need to decrease the number of questions per session or to increase the time length of the training sessions after changes in Session 1 take place.

- Participants need to be assigned to training treatments based on their cognitive tests scores, therefore keeping the cognitive skills of both groups at the same level.

8.3 Study 3 Design

8.3.1 Task

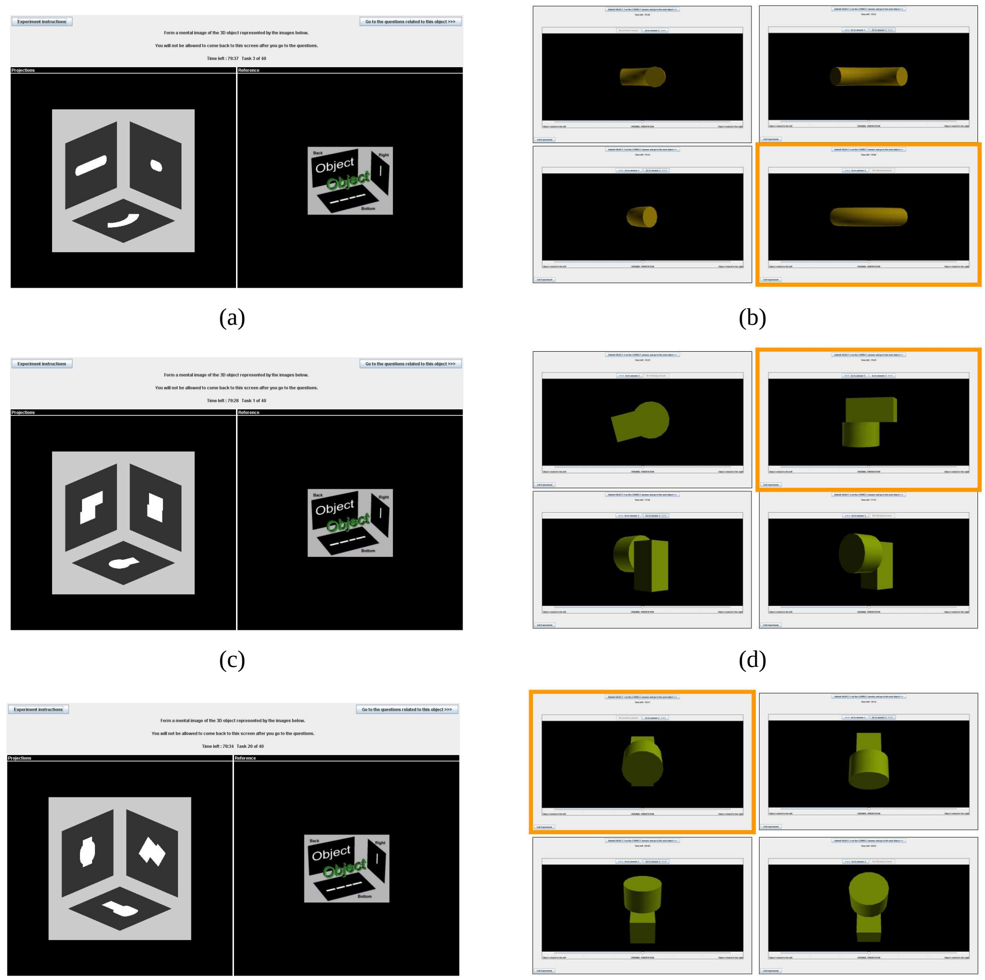
Each visualization question consists of two screens: the *analysis screen* and *the selection screen*. The analysis screen displays the three orthogonal projections and instructs the participants to form a ”mental image” of the 3D objects based on the 2D projections, paying particular attention to shape and orientation. Once participants consider that they have developed the best possible mental representation of the object, they proceed to the selection screen. In the selection screen, participants are asked to select from a set of four 3D object, the one that best fits the mental image they formed. The objects are presented in sequence one object at a time. They can also be rotated ±90deg around the vertical axis, improving viewers ability to perceive fine orientation differences between 3D objects. Participants can browse back and forth between the four 3D objects before finally selecting an answer. However, they are not allowed to see the 2D projections after leaving the projection screen.

8.3.2 Stimuli

The goal of the training procedure is to improve the strategies used by visualizers when faced with the task of reconstructing a 3D object based on three flat shaded outlines projected in three walls (i.e., x-y plane, x-z plane and y-z plane). The three projections are displayed in-place, that is, they are shown parallel to their corresponding planes in 3D space as seen in Figure 8.3.1 . The in-place presentation is expected to reduce the cognitive load, particularly for subjects with low spatial ability. Since the projections are shown in 3D space, it is not necessary for viewers to do these mental transformations.

The complexity of each visualization question is a combination of the complexity of the projections and the configuration of the false answers. Complexity of the projections is calculated according to the geometric properties of the object (e.g., number of faces) and the properties that are hidden in the 2D projections (e.g., hidden edges or corners). The analysis of the errors

All the visualization questions were generated by combining the properties of the projected objects and the properties of the false answers:



(a) (b)

(c) (d)

(e) (f)

Figure 8.2: visualization questions used in the training experiment. Figures 8.2(a), 8.2(c) and 8.2(e) correspond to the *analysis screens* were the three in-place projections are displayed. Figures 8.2(b), 8.2(d) and 8.2(f) show the four objects given as possible answers. The objects are shown sequentially in the *selection screen*. The correct answers appear highlighted. Note that the projections shown in Figures 8.2(c) and 8.2(e) correspond to the same 3D object with different orientation.

1. Properties of the projected object in order expected difficulty:

   - Object's axis aligned to the x, y or z axis
   - Object rotated 45 degrees with respect to one axis
   - Object rotated along two axes

2. Properties of the false answer objects:

   - Course rotation: Objects with 90 degree rotation difference

- Mirror objects: Objects in mirror positions
- Precise rotation: Objects with 45 or 30 degree rotation difference
- Minimal perceived rotation: Objects with less than 30 degree rotation difference

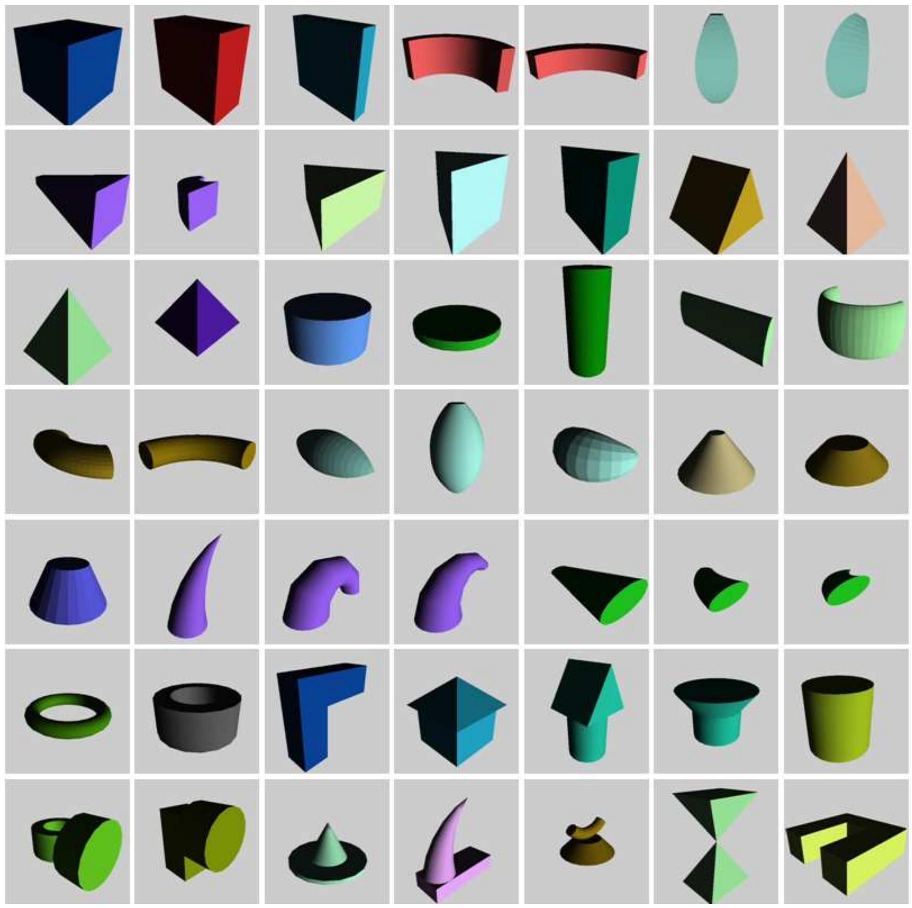


Figure 8.3: Set of 49 objects used on Study 3: 14 objects (2 bottom rows) are composed by tow or more geons.

All questions in the visualization training methods can be grouped according to the frequency in which they appear in each training method. A total of 98 unique questions were created to be used in training. A total of 57 questions appeared only once during training, but they were used in the incremental and the unstructured methods. The participants'performance in this set of visualization questions is expected to reflect the differences in training effect between training methods. A second set of 28 questions appeared at least twice in a training method, and with them we can capture how learning progresses within each training method. Finally, 13 questions appear only on the incremental or the unstructured training, but not in both. These questions were added to the training to capture differences in performance between participants that had training and those who did not.

8.3.3 Participants

Forty-four students (20 females and 24 males) from Rutgers University, New Brunswick campus took part on the study. The graduate and undergraduate students were recruited from fours campuses through flyers. All participants that completed all five experiment sessions received a 64 MB USB thumb drive. In addition, students were divided in groups based on the date of completion of the experiment, and they participated in the raffle of an iPod mini. Three iPods were raffled in this study. Only two students decided to terminate their participation early due to scheduling conflicts.

Participants read the experiment description and subject consent form at the beginning of each experiment session. In the first experiment session, participants also answered a basic demographic questionnaire and took two paper-based tests of spatial abilities.

8.3.4 Experimental Setup

Ordered Incremental Training

Two training treatments were developed in Study 3: ordered incremental training and unstructured training. Both training treatments are divided in five sessions and present the same questions. The treatments differ in the order the visualization questions are presented. The ordered incremental training method presents visualization questions in increasing order of difficulty using the visual properties described in Section 8.3.2 to quantify difficulty. The unstructured training present the same visualization questions in a randomly assign session and position. The experiment consisted of five sessions which took place between 1 and 3 days apart. The structure of all sessions is described below:

Session 1 is an introductory session. Participants reviewed materials that explained the nature of the visualization questions, they were introduced to the software interface, and they were asked to answer 12 visualization questions. These questions are not considered part of their training. The procedure in session 1 was the same for the both the incremental and unstructured training sessions.

Session 2 gives participants 30 questions to answer with no time limit. It begins by presenting single geons aligned to the main projection planes as showed in Figure 8.4.a. The complexity of the questions was increased by using geon-based structures and large rotations (between 90 and 45 degrees) around one axis as demonstrated in Figure 8.4.b. Towards the end of the session, mirror answers are introduced for objects aligned to main projection planes (seen in Figure 8.4.c) or objects rotated 45 degrees or less as shown in Figure 8.4.d.

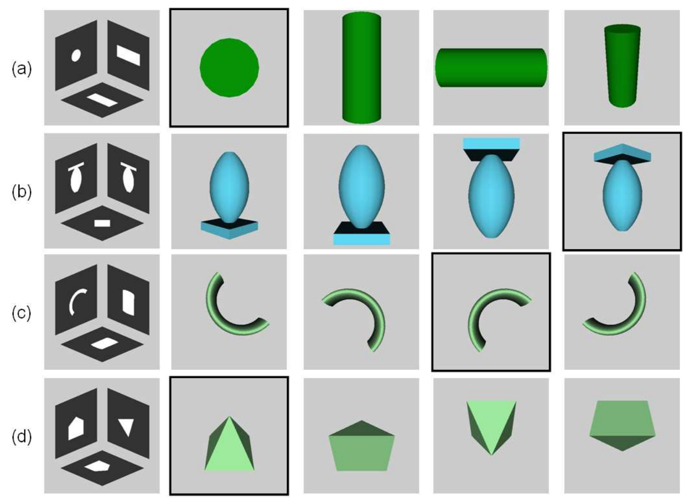


Figure 8.4: Characteristic visualization questions from session 2

Session 3 consisted of 40 visualization question. The first 8 questions were representative of the properties practiced in session 2. In this session, three different properties are trained: objects with 30 to 45 degree rotation in one axis. The possible answer were objects between 45 to 90 degrees away from the correct answer or objects in mirror orientations (e.g., Figure 8.5.a). Questions with objects rotated between 45 and 90 degrees in two axis were then introduced as illustrated (Figure 8.5.b). Towards the end of the session, a few examples of questions with objects rotated 30 or 15 degrees in one axis with choices at 30 or 15 degrees away from correct answer were given to participants. Figure 8.5.c is an example of the later type of question.

Session 4 contained 40 questions. The focus of this session is training in the visualization problems that are expected to have a high difficulty level. That is, questions with objects with rotations between 45 and 90 degrees in two axes (Figure 8.6.a) and questions with objects

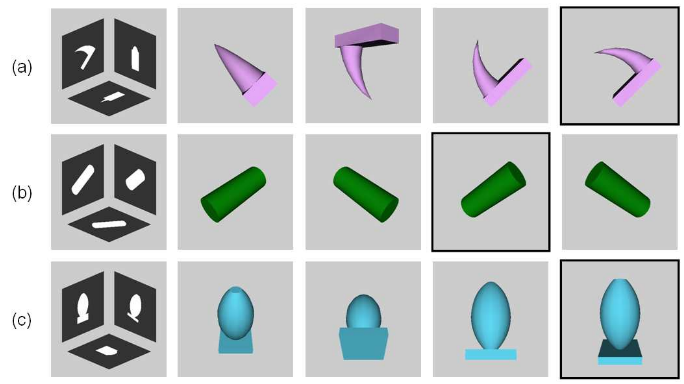


Figure 8.5: Characteristic visualization questions from session 3

rotated 30 and or 15 degrees (Figure 8.6.b). In both cases, answer possibilities contained images with rotations of 30 degrees or less away from correct answer and mirror images.

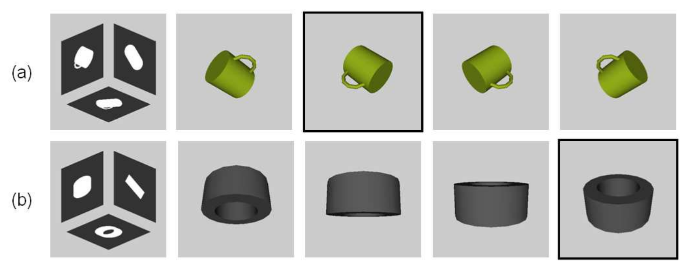


Figure 8.6: Characteristic visualization questions from session 4

Session 5 concludes the training with a set of 20 questions where 1 or 2 examples of each set of properties presented in all the previous sessions. No new properties are introduced in this session.

Ordered incremental training is different from the commonly used structured training in that it does not provide feedback to the experiment participants after they answer each questions. Instead, incremental training presents a short summary of how many correct questions were answered in each session. The decision of now using feedback after each visualization question has significant effects in the interpretation of the results from Study 3. On the one hand, feedback has been shown to improve the results from training because it encourages experiment participants to improve, but more importantly, it facilitates the development and re-structure of problem solving strategies. On the other hand, feedback can encourage the development of strategies based on visual pattern matching between the projections and the answers. Having no feedback also resembles the development of strategies based on everyday use of visualization, where no feedback regarding the accuracy of the visualization comprehension is available. Because the goal of this study is to determine if the visual properties can be use to accurately measure the difficulty of the visualization questions based on the differences between training treatments, rather than to obtain the best improvement possible, it was decided not to use feedback after each question for both training treatments.

Frequency of visualization questions

Ninety-eight visualization questions were created for this study. Most of the visualization questions (87) were used in both training methods, while a small set of 11 questions appear only in one of the training treatments. Visualization questions can also appear once or multiple times within a training treatment. Based on these two characteristics, the 98 question can be classified as:

- One instance in both training methods: 56
- Multiple instances in both training methods: 31
- One instance in one training method: 8
- Multiple instances in one training method: 3

Figure 8.7 shows how many questions (based on frequency) are used in each session for both training methods. The distribution of the visualization questions on the incremental training method is intentional, while the distribution of questions on the unstructured training is the result of a random re-order of the questions.

Since all test questions on the unstructured training were randomly re-ordered, many of the questions appear in very different positions compared to the incremental training method. In fact, no visualiztion question remained in the same position and session in both treatments. However, the positions of some questions in both treatments are close enough for analysis purposes. A total of 19 questions were found to be no more than 13 questions appart, that is the distance of the same question in both treatments is less than 10 percent the total number of

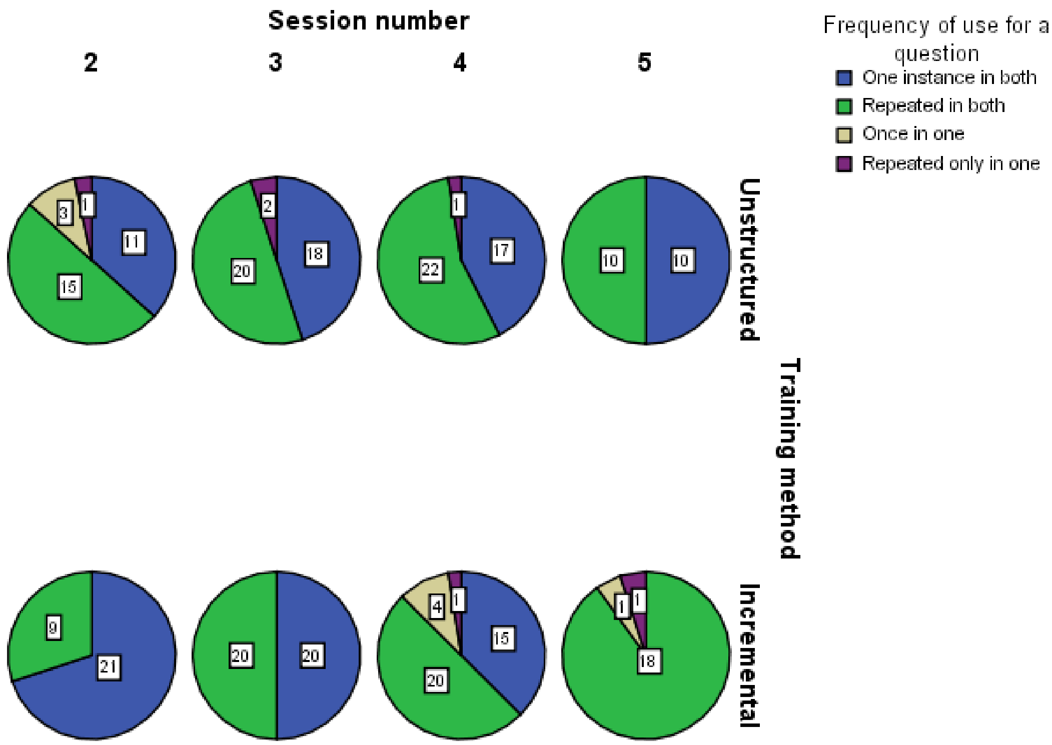


Figure 8.7: Distribution of questions in all sessions for both training methods. Visualization questions are classified according to how many times they are used within the same training treatment, and if they are used in both training methods or only one.

questions particiants answer in training. The questions were found on all sessions: 4 questions in the second session, 6 in the third session and the fourth session, and 3 questions in session 5.

8.3.5 Measuring Training Effects

Performance of experiment participants is defined in terms of the accuracy and the time invested in the construction of a mental picture of the object represented by the multiview projections. This study used two dependent variables:

- Time of analysis (ToA): Time (in seconds) that participants spent analyzing the orthogonal projections
- Accuracy (Acc): Accuracy of the 3D object selected as the answer (it has a value of 1 if the selection is correct, 0 if it is not)

The general spatial skill of participants was measured with two tests of spatial abilities: Mental Rotation Test (M.R.T. Test) and the Paper folding Test (VZ-2 Test). The tests were scored based on the percentage of correct and incorrect answers in all the test items and all the answered test items.

The independent variables are spatial skill (low, medium, high), training treatment (incremental, random), and question set (2 to 5). The two spatial factors what were found in experiment 1to have the highest correlation to visualization comprehension were measured again in this study. Spatial visualization was measured with the Paper Folding Test and spatial orientation was measured with the Vandenberg Mental Rotation Test (M.R.T. Test). Instead of using a unique score for the test, the count of items answered, number of correct and incorrect answers, and percentage of correct and incorrect answers given the total of items answered were used. Resent research favors recording these three values instead of assigning a single numeric score [26].

8.3.6 Procedure

Participants were asked to take part in five experiment sessions with 1 to 3 days between consecutive sessions. The participants were given a written experiment description, informed consent form, questionnaire, spatial ability tests, detailed introduction to visualization test, example questions and preliminary test with 12 visualization questions. These visualization visualization questions were randomly selected from all the training sessions and were used with the results from the spatial ability test to assign participants to one of the training groups. The goal was to obtain two training groups with no significant skill differences before training.

Participants were assigned to different training groups based on the scores in their spatial ability tests (i.e., Mental Rotation Test and Paper Folding Test) and their accuracy in the 10 random visualization questions given on *Session one*. This controlled assignment helped to generate two initial groups with no significant differences in spatial abilities.

Experiment participants completed five training sessions where they answered 130 visualization questions. In *Session one*, after informed consent was obtained, participants were given a questionnaire. The questionnaire recorded ethnographic information, computers use and general spatial activities information [64].

Then, participants completed two paper-based tests of spatial ability (Vandenberg Mental Rotations test and Paper Folding test). Once participants complete the spatial ability tests, they reviewed the instructions explaining the Projection Visualization Test and the visualization task expected from them and completed 10 practice visualization questions (with feedback regarding the correct answer). They proceeded to answer 10 randomly selected visualization tests and their score (i.e., accuracy of their answers) is used to assign them to structure or unstructured training. The experimenters assisted the participants during the instructions and practice to make sure that the visualization test and procedures were clearly understood. All the verbal explanations given by the experimenters were scripted. Session one took between 45 and 100 minutes to be completed.Sessions 2, 3 and 4 consisted exclusively of experimental visualization questions and they required little or no intervention from the experimenters. Session 2 consisted of 30 visualization questions while Session 3 and Session 4 had 40. Finally, Session 5 presented 20 visualization questions that were followed by a second set of paper-based spatial ability tests.

In every session, participants were instructed to be as accurate as possible, without overextending the time used to answer the visualization questions. A time limit of 80 minutes was imposed to answer up to 40 questions. However, this time is enough to allow all the participants to answer all visualization questions presented in the session.

8.4 Hypothesis and Expected Results

It is expected that participants in the ordered incremental training will exhibit more general projection visualization comprehension skills than those on unstructured training. Neither incremental nor unstructured training is expect to improve an individuals spatial abilities. The visualization questions used in training are a particular type of projection visualization, where only orientation is evaluated making the training very specific. Training in very particular visualization tasks has been shown to have limited or no transfer of skill to the tests of spatial ability used in this study [87], [70].

Spatial abilities were shown to be related to visualization comprehension in the Projection Visualization Test, therefore it is expected that the scores of the Paper Folding test and the

Vandenberg Mental Rotation Test will be related to performance in the visualization test (i.e., accuracy and time). In particular, total counts of correct and incorrect items in the spatial ability tests are expected to have the highest correlation to ToA and ToS in the Projection Visualization Test, while percentage of correct and incorrect items in the spatial ability tests are expected to correlate to accuracy in the Projection Visualization Test. The reason for these expectations is that the spatial ability tests are time constrained, and participants that are "slow" but accurate will have low item counts in the spatial ability test while percentages better reflect their accuracy.

The hypotheses regarding spatial ability and visualization comprehension are as follows:

[*H1a*] There will be a significant positive correlation between the total count of items answered in the Paper Folding Test and the ToS in the Projection Visualization Test.

[*H1b*] There will be a significant positive correlation between the total count of items answered in the Mental Rotation Test and the ToS in the Projection Visualization Test.

[*H1c*] There will be a significant positive correlation between the total count of items answered in the Mental Rotation Test and the ToA in the Projection Visualization Test.

[*H1d*] There will be a significant positive correlation between the total count of items answered in the Paper Folding Test and the ToA in the Projection Visualization Test.

[*H2a*] There will be a significant positive correlation between the percentage of correctly answered items in the Paper Folding Test and the accuracy in the Projection Visualization Test.

[*H2b*] There will be a significant positive correlation between the percentage of correctly answered items in the Paper Folding Test and the accuracy in the Projection Visualization Test.

In addition to predicting the correlations between spatial ability and accuracy, it is expected that there will be improvement in visualization comprehension in both training treatments. However,incremental training is expected to have significantly better training outcomes in every question set, reaching a ceiling performance in the last sets because those questions will be hard regardless of cognitive skill and training. Thus, it is predicted that:

$$
\begin{aligned}
& (\quad QuestionSet4\_incremental_{improvement} > QuestionSet4\_unstructured_{improvement}) \\
\approx \quad & (QuestionSet3\_incremental_{improvement} > QuestionSet3\_unstructured_{improvement}) \\
> \quad & (QuestionSet2\_incremental_{improvement} \approx QuestionSet2\_unstructured_{improvement}) \\
> \quad & (QuestionSet1\_incremental_{improvement} \approx QuestionSet1\_unstructured_{improvement})
\end{aligned}
$$

Where ">" means "higher significant improvement" and $\approx$ means "equivalent to". Both training methods are expected to increase accuracy in the first three Question Sets, but significant increase in not expected in Question Set 4 given that it contains the visualization questions of highest difficulty. When comparing both training methods, it is expected that incremental training will show significant higher improvement in accuracy after the second question set, since the Question Sets 1 and 2 have the visualization questions with lowest difficulty level. The next set of hypotheses indicates this:

[*H3a*] Percentage of accurate answers in Question Set 2 of the incremental training will be significantly higher than percentage of accurate answers in Question Set 1 of the incremental training

[*H3b*] Percentage of accurate answers in Question Set 3 of the incremental training will be significantly higher than percentage of accurate answers in Question Set 2of the incremental training

[*H3c*] Percentage of accurate answers in Question Set 4 of the incremental training will be significantly higher than percentage of accurate answers in Question Set 2 of the incremental training

[*H4a*] Percentage of accurate answers in Question Set 2 of the unstructured training will be significantly higher than percentage of accurate answers in Question Set 1 of the unstructured training

[*H4b*] Percentage of accurate answers in Question Set 3 of the unstructured training will be significantly higher than percentage of accurate answers in Question Set 2 of the unstructured training

[*H4c*] Percentage of accurate answers in Question Set 4 of the unstructured training will be significantly higher than percentage of accurate answers in Question Set 2 of the unstructured training

[*H5*] Accuracy in Question Set 3 will be significantly higher in participants in incremental training in comparison with participants in unstructured training

[*H6*] Accuracy in Question Set 4 will be significantly higher in participants in incremental training in comparison with participants in unstructured training

8.5 Results

Performance of participants in the visualization task was measured in terms of the accuracy of the time spent analyzing the 2D projections (ToA) and their answers accuracy (Acc). Participants were classified as spatial skill levels (i.e. low, medium and high) were determined based on the scores obtained in two standard tests of visual-spatial ability: Mental Rotation Test (M.R.T. Test) and the Paper folding Test (VZ-2 Test). A set of non-parametric statistical test was used to study the performance and spatial skill data, in order was to establish whether if there were significant differences between both training treatment groups, and how does training affect participants with different spatial ability skills.

8.5.1 Questionnaire Results

The average age of the experiment participants is 20 years, with ages ranging between 18 and 34 years. Only two of the 44 participants were graduate students and most participants came from engineering, science and humanity fields as shown on Figure 8.8.

All participants use computers in a regular basis and reporter between 1 to 18 years of experience, with an average of 10 years. All participants had experience in word processing, Internet browsing and email management. Eight participants reported experience in 3D graphics and modeling (e.g., CAD and mechanical drawing). Forty-one of the participants reported

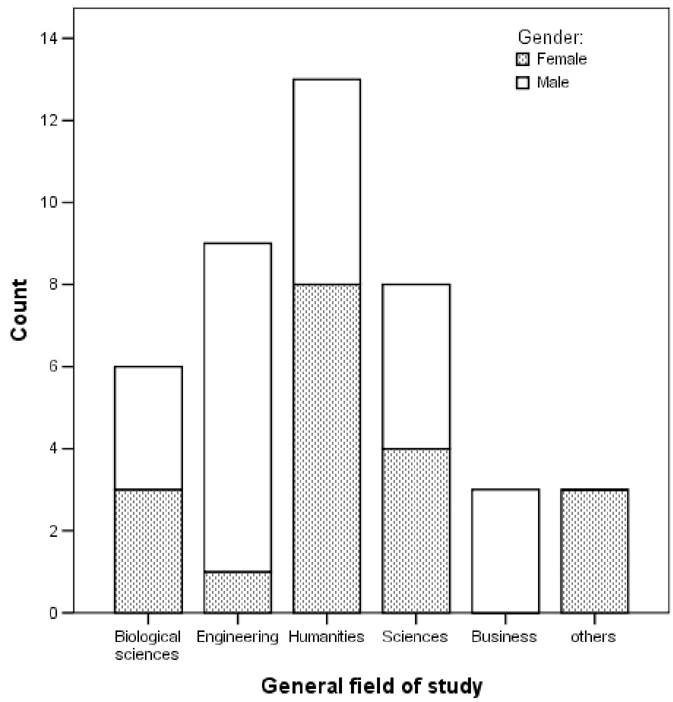


Figure 8.8: Field of study and gender of the 44 participants on Study 3

to have video game experience. The average was 10 years of experience. One participant did not have video game experience.

8.5.2 Participant Skills and Group Assignment

The spatial skill of participants was measured with two standardized test of visual spatial ability: The Paper Folding Test (VZ-2) and the Shepard and Metzler Mental Rotation Test (MRT). Exploratory analysis found that the test scores were not normally distributed, therefore non-parametric test are used in the analysis of the data.

Experimenters assigned participants to one of the training treatments based on the scores (i.e., percentage of correct answers in all test questions, percentage of correct answers in all answered questions, percentage of incorrect answers in all test questions, percentage of incorrect answers in all answered questions and guess-adjusted score) of the Paper Folding Test and Mental Rotation Test.

The spatial skills of participants in the incremental and unstructured training groups were compared using a Mann Whitney U test and no significant differences were found between

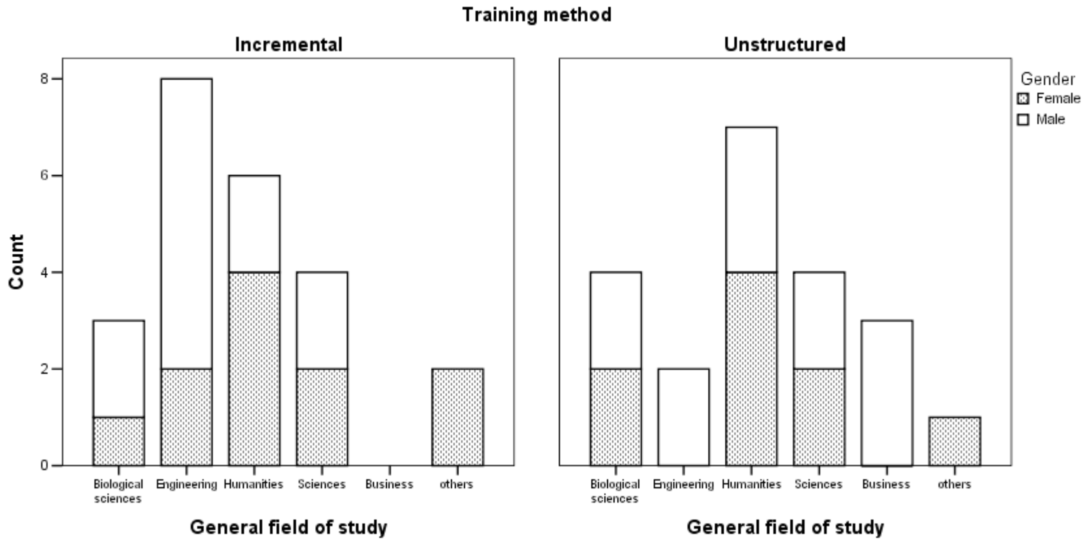


Figure 8.9: Field of study and gender of experiment participants in the incremental and structured training methods. Each bar shows the number of males and females from each field of study.

both training groups in any of the scores of the spatial ability tests. Figure 8.9 shows the field of study and gender of participants in the incremental and unstructured training.

8.5.3 Incremental vs. Unstructured Training

Two measures of performance were collected in the visualization training: time of analysis (ToA) measured in seconds and accuracy of the participants answers (Acc). The variable accuracy has a value of 1 if a participant's answer to a particular visualization question is correct, 0 otherwhile. Accuracy becomes the percentage of correct answers when the variable is summarized by participant or by question. Table 8.3 presents the basic descriptive statistics of ToA and Acc for questions that appear once or multiple times in both training methods.

The normality of both performance variables was tested by means of a Shapiro Wilk test. The results from this test revealed that accuracy ($W = 0.857$, $df=44$, $p<0.00$) and time of analysis ($W = 0.829$, $df=44$, $p<0.00$) are not normally distributed, therefore non-parametric tests will be used int he data analysis. It was also found by means of a Spearmans rho coefficient that time of analysis and accuracy are not significantly correlated ($r = 1.83$, $p<0.118$). This result implies that both variables can be analyzed independently.

Table 8.3: Descriptive statistics of performance measures in all questions of the visualization training methods.

			Frequency of Visualization Questions in Training Treatment			
			Once		Multiple Times	
			ToA(sec)	Acc(%)	ToA(sec)	Acc(%)
Incremental	(n=22)	Mean	20.33	0.74	20.56	0.75
		Median	15.44	0.75	16.44	0.80
		S.D	10.37	0.11	11.34	0.10
		Max.	45.54	0.93	50.06	0.87
		Min.	8.21	0.50	9.32	0.49
Unstructured	(n=22)	Mean	14.87	0.65	15.78	0.65
		Median	14.93	0.73	15.09	0.70
		S.D.	5.42	0.21	5.73	0.22
		Max.	25.36	0.25	26.37	0.89
		Min.	5.57	0.90	6.33	0.16

Visualization questions used in both training methods

The analysis of performance in the 57 questions that appeared once in each training method, it was found that participants in the incremental training were significantly more accurate and faster in the analysis of the projections. A Mann-Whitney revealed differences in percentage of correct answers (U = 1044, $p < 0.001$) and time of analysis (U = 655, $p < 0.000$) between both training groups.

As mentioned in section 8.3.4, 19 were considered to be in similar positions in both training methods. Significant differences in accuracy (Mann-Whitney U= 96.5, $p < 0.014$) were found in favor of participants in the incremental training. This result suggests that it is the nature of the preceding visualization questions and not only their positions that causes the incremental training to have higher accuracy.

The time spent by participants in the incremental training is significantly higher compared to the unstructured training. Since literature in cognitive spatial analysis links time to strategy [36], this result may suggest that the incremental training method is helping in the development or the application of spatial strategies different to those used by participants in the unstructured training.

The analysis of the set of visualization questions that appeared twice in both training sessions is a follows. A Wilcoxon Test of related samples found significant improvement in accuracy for the repeated questions in the unstructured test (Z=-2.274, $p < 0.023$) and no significant differences were found in accuracy for the incremental training treatment (Z = -0.469,$p <$

0.639). This finding suggests that incremental training participants received enough training before the first use of the question to achieve the levels of accuracy early in the training. A Mann-Whithney Test (U = 157233, $p < 0.000$) found significant differences between the accuracy in the answers of repeated questions in their second showing in the incremental training.

8.5.4 Spatial Ability Factors and Training

To determine if differences in participants' spatial ability skills affected their performance in the visualization test, first participants were classified in three groups according to their scores. A Spearman's rho correlation analysis found that the scores with the highest correlation to accuracy were the percentage of correct answers in all answered questions for the Mental Rotation Test, and the percentage of incorrect answers in all the test questions for the Paper Folding Test respectively. Both scores were used to assign participants to three levels of spatial ability as follows: 15 low, 18 medium and 11 high. Scores within one standard deviation around the mean were considered to be part of the medium skill group.

Figure 8.10 shows the average percentage of correct answers in both training method by participants in the three levels of spatial ability for the questions that appeared once in both training methods. A series of pair-wise comparisons of the different levels of spatial ability were done using the Mann Whitney Test. Significant differences between all levels of spatial skill within the incremental training, and between the high and medium levels on the unstructured training.

As seen in Figure 8.11, no significant differences in time of analysis across spatial ability level were found for the set of questions that were used one in each. There were no significant differences in time of analysis between all levels within the incremental training, but significant differences were found between the low level and all the other levels with in the unstructured training.

We conclude the analysis of the data by comparing the scores obtained in the spatial ability tests (e.g., Mental Rotation Test and Paper Folding Test) before and after the training sessions. We computed the following scores:

- Percentage of correct answers in all test items

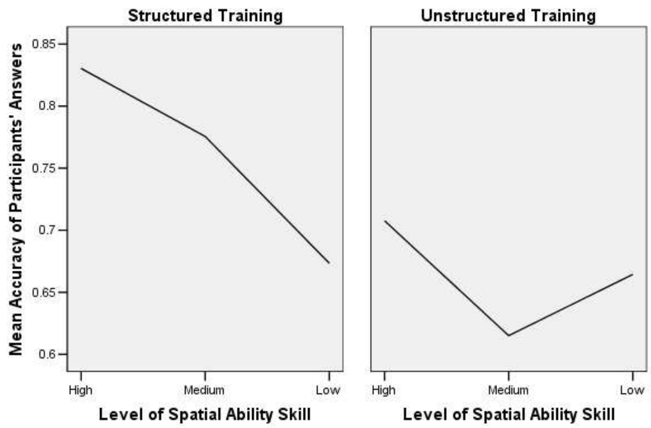


Figure 8.10: Percentage of correct by training method and spatial ability level for the questions that appeared once in both training methods.

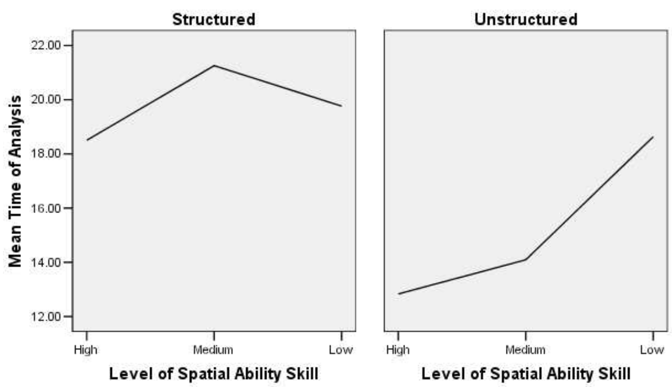


Figure 8.11: Average time of analysis by training method and spatial ability level for the questions that appeared once in both training methods.

- Percentage of correct answers in all answered questions
- Percentage of incorrect answers in all test questions
- Percentage of incorrect answers in all answered questions

A Wilcoxon test of paired samples revealed that both percentages of correct answers were significantly higher and both percentages of incorrect answers were significantly lower on the post-test analysis. It cannot be conclude from these results that transfer of skill was obtained, because this improvement can be the result of the subjects improving their test taking strategy. Given that the percentage of correct questions increased and the percentages of incorrect answers was significantly reduced in the incremental treatment group, the results suggests that there may be improvement in the skill required to solve the spatial ability tests.

8.6 Discussion of Results

An ordered incremental training method was tested in order to determine if the properties uncovered in Chapter 7 could be used to quantify the difficulty of visualization questions. In general, it was found that participants in the incremental training group were significantly more accurate and slower in the analysis of the visualization questions than participants in unstructured training. It was also found that participants with low scores in the spatial ability benefited the most from the incremental training.

The incremental training can be considered minimal training, because it used only incremental difficulty of the visualization questions as a training strategy. These results are promising, in particular because the effects of training uncovered were strong enough to be detected in a low-size sample and high variability.

8.7 Chapter Summary

This chapter showed how the properties identified in Chapter 7 were used to design a training method were those properties are introduced one at a time. This training strategy was expected to improve individual's visualization comprehension better than methods were no specific order is followed. This chapter presented the results from a partial analysis of the data collected in the experiment. It was found that participants assigned to incremental training showed significantly higher accuracy in the visualization test. In particular, low spatial ability subjects were found to benefit more from the incremental training than from the unstructured training.

Table 8.4 presents a summary of the results in terms of the hypothesis postulated on section 8.4.

Table 8.4: Summary of results based on initial hypothesis and research questions .

	Hypothesis or Questions	Confirmed
H1c	There will be a significant positive correlation between the total count of items answered in the Mental Rotation Test and the ToA in the Projection Visualization Test	No
H1d	There will be a significant positive correlation between the total count of items answered in the Paper Folding Test and the ToA in the Projection Visualization Test	No
H2a	There will be a significant positive correlation between the percentage of correctly answered items in the Paper Folding Test and the accuracy in the Projection Visualization Test	Yes
H2b	There will be a significant positive correlation between the percentage of correctly answered items in the Paper Folding Test and the accuracy in the Projection Visualization Test	Yes
H3a	Percentage of accurate answers in Question Set 2 of the incremental training will be significantly higher than percentage of accurate answers in Question Set 1 of the incremental training	Yes
H3b	Percentage of accurate answers in Question Set 3 of the incremental training will be significantly higher than percentage of accurate answers in Question Set 2of the incremental training	Yes
H3c	Percentage of accurate answers in Question Set 4 of the incremental training will be significantly higher than percentage of accurate answers in Question Set 2 of the incremental training	Yes
H4a	Percentage of accurate answers in Question Set 2 of the unstructured training will be significantly higher than percentage of accurate answers in Question Set 1 of the unstructured training	Yes
H4b	Percentage of accurate answers in Question Set 3 of the unstructured training will be significantly higher than percentage of accurate answers in Question Set 2 of the unstructured training	Yes
H4c	Percentage of accurate answers in Question Set 4 of the unstructured training will be significantly higher than percentage of accurate answers in Question Set 2 of the unstructured training	Yes
H5	Accuracy in Question Set 3 will be significantly higher in participants in incremental training in comparison with participants in unstructured training	Yes
H6	Accuracy in Question Set 4 will be significantly higher in participants in incremental training in comparison with participants in unstructured training	No

Chapter 9
Conclusions

This dissertation presented an approach for determining the factors that allow quantification of visualization comprehension difficulty for individuals from diverse populations. This knowledge is fundamental to the development of the skills needed by viewers of scientific and information visualizations. This dissertation also proposed that formal training is required for the development of visualization literacy in the general population, and defined *Visualization Literacy* as the set of skills and strategies required to successfully interpret modern scientific and information visualizations.

9.1 Summary of Results

The main result from this work is the validation of an approach that leads to a set of visual properties that affect an individual's ability to accurately interpret a visualization. These properties, in turn, allow a quantitative ranking of the visualization problems from easy to hard, so they can be used to set up effective training methods that address the needs of diverse populations. The main results from each step in the approach are listed below.

Step 1 : Cognitive Factors that Affect Visualization Comprehension

1. Visualization comprehension issues were found to affect even educated college students in the peak age range for cognitive skills development. Factors such as lack of formal education and age are likely to negatively intensify comprehension problems in diverse populations.

2. Significant gender differences were found in the accuracy of the answers given in the visualization test. However, no significant gender differences were captured by any of the psychometric tests in Study 1.

3. The strength of the correlation between the cognitive abilities and visualization questions was not constant across all visualization questions. The nature of the set of possible answers in some of the questions made them more difficult for individuals with lower, or in the case perceptual speed, higher skill levels.

4. The time participants spent analyzing a visualization question is not correlated with the accuracy of the visualization analysis (i.e., mental reconstruction of objects' shape and orientation). Individual differences and the strategies used to solve the problems may have contributed to the time differences.

Step 2: Visualization Comprehension, Visual Properties and Strategies

1. Significant differences in the accuracy of participants'answers were found between those with low and those with high levels of spatial skill, as measured by the Paper Folding Test.

2. Geometric characteristics of the visualized object (e.g., number of edges and surfaces of the 3D object) and visual properties (e.g., hidden edges in the 2D projections) in visualization questions were found to make visualization questions significantly more difficult to analyze for most participants with low spatial skill.

3. The visual information and the strategies used by novices and expert visualizers can be very different. It was found that participants with lower accuracy were not integrating the visual information provided by all the 2D projections and usually relied on one projection.

Step 3: Effect of Incremental Training on Visualization Comprehension

1. Incremental training improves viewers' visualization skill with only minimal training using a training strategy that is based on incremental difficulty of the visualization questions as a training strategy.

2. Participants at all levels of spatial skill improved after training in the incremental treatment. There were significant differences in accuracy between all levels of spatial skill.

9.2 Limitations of Research

Bellow we discuss some limitations of this research:

1. It is difficult to get high variability in spatial ability for a representative sample of participants

   It was desired to study the effect of structured training on the full range of spatial ability found in the human population. However, subjects were drawn from the undergraduate population at Rutgers University. As such, there was little representation of individuals with very low spatial skills because all participants had significant prior computer and video game experience.

2. Gender and field of study can be confounded

   Although an equal number of men and women were used in the experiment, the men typically came from engineering and computer science whereas the women tended to come from biology, the humanities or the arts. Since engineers and computer scientists use visualizations in their field of study, they were likely to be more familiar with the visualizations and also have higher spatial skills.

3. There are no existing algorithms for selecting and categorizing visualization properties associated with user comprehension

   The visualization properties found in the projection visualization were gathered by trial and error. They were aided by the sub-categorization into classes of difficulty and the correlation analysis, but a more general method needs to be found for this work, in particular, because it is likely that the properties of complex visualization will interact with each other in terms of a user's ability to comprehend the visualization. In short, what is needed is a theory as to why Visualization A might be easier than Visualization B. This work is a step in the right direction but more research is needed.

4. Assigning and classifying participants by spatial ability was imprecise because the existing spatial ability tests are low resolution

   Performance measures on the spatial ability tests developed in Psychology represent a statistical average. Any individual performance can be, on a given day, widely deviant from the average score of this person. Thus, it was found that some of the subjects who were matched with other subjects to be of the same spatial ability actually had much higher spatial abilities, therefore losing some of the control in the incremental training experiment.

5. No true mass practice

   Skill transfer requires the acquisition of a large knowledge base and massive amounts of learning time. The studies that were run was limited to to five sessions. This is most certainly why some subjects did not show changes in their basic spatial abilities. It is unclear, without further work, how much practice is needed to gain visualization literacy nor how many different types of visualization problems would be required in the training.

6. No fully developed training was administered

   In Study 1, the projection was displayed as a mosaic. This was changed to an in-place visualization in Study 3. The answers were also changed from a single screen presention to sequential screens presentation. This was done because the mosaic visualization might have affected the subjects comprehension of the visualization, possibly when the visualizations became more complex. This would have affected the sorting of the visualizations into categories of difficulty and possibly the identification of the important comprehension properties. Displaying the answers all at once may have added to the cognitive load of the subject's task and affected the time spent in this part of the task. In addition, the sequential presentation gave time spent on each potential answer which could be used to help determine the key problem the subject was having with the comprehension.

9.3 Contributions

The research is expected to generate a set of major contributions to the Field of Visualization. The significant contributions are listed below. As with all research, the process of conducting the research generates a set of lesser contributions, for example, an experiment is designed to control for a particular human cognitive problem in a somewhat different way than other experiments. Although the adapted experiment design is useful, its contribution is not earthshaking.

These lesser contributions are listed below as subsets of the significant contributions.

Significant Contributions:

1. Defined what Visualiztion Literacy is
2. Demonstration of a viable method for training people in visualization literacy
   - demonstrated that structured training of visualization properties improves visualization comprehension better than unstructured training
   - demonstrated retention of trained visualization comprehension skills
   - developed a visualization comprehension test
   - developed a possible way for understanding what visualization literacy is and for training people in visualization literacy
3. Demonstrated that spatial ability measures are necessary for studying visualization comprehension
   - found the spatial ability tests that correlate with projection visualization
   - found a set of spatial ability tests that do not correlate with projection visualization
4. Formulated a method for examining visualizations to determine what comprehension strategies they require of users
   - developed a method using spatial ability and a visualization comprehension multiple choice test to select out specific difficulties users might have with visualization
   - developed a cognitive model of visualization comprehension
   - tested cognitive model of visualization comprehension against user data

9.4 Publications Generating and Stemming from Research

The following is the list of publications generated by this research work:

1. **Maria C. Velez**, Deborah Silver, Marilyn Tremaine. *Beyond Evaluations: Understanding How and Why Visualizations Work*. Paper in progress.

2. **Maria C. Velez**, Deborah Silver, Marilyn Tremaine, Karen Bemis. *Visualization Literacy: A Novice's Guide to Visualization*. Best Poster Award at the IEEE Information Visualization Conference, 2008.

3. **Maria Velez.** *Visualization Diversity: A Cognitive-Based Training Method for Visualization Comprehension*. IEEE Visualization/VAST Doctoral Colloquium at IEEE Visualization 2006 in Baltimore, MD, October 2006.

4. **Maria Velez**, Deborah Silver, Marilyn Tremaine. *Understanding Visualization through Spatial Ability Differences.* Proceedings of Visualization 2005. IEEE, pages 511-518. Minneapolis, Min. 23-28 Oct, 2005.

5. Marilyn Tremaine, **Maria Velez**, Aleksandra Saracevic, Dezhi Wu, Bogdan Dorohonceanu, Allan Krebs and Ivan Marsic.*Does Size Matter: Gender and Platform Effects in Collaborative Problem Solving*. Proceedings of the 38th Hawaii International Conference on Systems Sciences HICSS 2005, Big Island, HI, CDROM and IEEE Digital Library http://www.ieee.org/), January 2005, 10 pages.

6. **Maria Velez**, Marilyn Tremaine, Aleksandra Sarcevic, Bogdan Dorohonceanu, Allan Krebs, and Ivan Marsic, *Who's in Charge Here?: Communicating Across Unequal Computer Platforms*, ACM Transactions on Human-Computer Interaction (TOCHI), Vol. 11 No. 4, 2004, 407-444.

7. **Maria C. Velez** *A Study on the Impact of Heterogeneous Platforms on Collaboration.* Unpublished Masters thesis, Department of Electrical and Computer Engineering, Rutgers, the State University.

9.5 Future Work

As with all research, one is never done: The more results that are found, the more questions that arise. This section describes the large amount of future research that needs to be done in order to expand the approach suggested in this thesis. Given that the thesis presents a new method and the limitations section of this chapter suggests that this method has not been fully tested, this list will cover only those key elements that need to be done and therefore is not exhaustive of all possible investigations that could take place.

First, only one visualizations has been examined. In addition, the visualization test generated for projection-based visualization used only a few representative objects and was necessarily simplistic. Many other scientific visualizations need to be explored as well as running a study that increases the complexity of the projection visualization test. In addition, information visualizations offer a rich category of possibilities. Visualizations of four-dimensional objects would also be a rich area to study.

Developing a comprehensive model of how an individual understands and builds a mental image of an object in the simplistic projection visualizations used in this thesis is a five-year research project by itself. This thesis has developed a simple model using three properties. As such, this model does not capture the complexities of this understanding. This is proposed for future work.

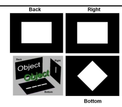
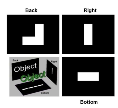
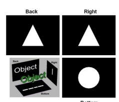
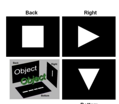
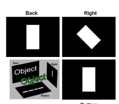
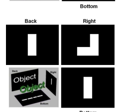
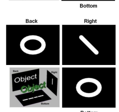
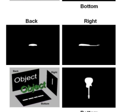
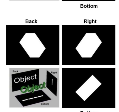
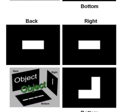
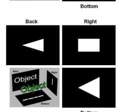
It is not known if visualization literacy is actually established through the training developed in this dissertation. Many things are not known, e.g., how much training is needed, what are the representative visualization problems to use in the training, what level to start the training at, given measured gaps in a trainees spatial abilities, etc. In addition, it is unlikely that the training will be either long or comprehensive enough to cause an improvement in basic spatial abilities. However, the training may still improve visualization literacy if done correctly, that is, the training is likely to transfer to a field such as geology. This suggests that future work should include the development of such general training in visualizations common to science and then test the transfer of the training to the understanding of visualizations in the field of interest.

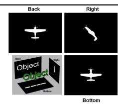
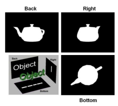
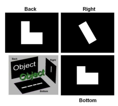
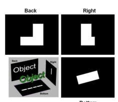
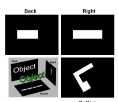
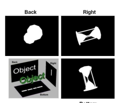
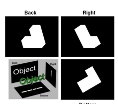
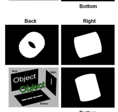
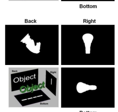
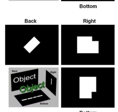
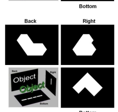
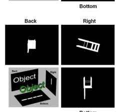
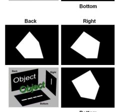
The training developed in the thesis assumed an order for the presentation of the visualization strategies being trained. This order was assumed from the visualization comprehension difficulty categorization. However this categorization is only a rough approximation. It may be that the order of these strategies is different than the order used. It may also be that order is irrelevant. It is possible that certain strategies need more training than others and a larger variation of examples of the strategy to be learned. This needs to be tested. An experiment which presents the strategy learning in various orders, removes some of the strategy learning and varies the training times needs to be run to further explore this area.

Appendix A
Index of Experiment Stimuli

The following tables show the visualization questions used in Study 1 and Study 3.

Table A.1: Visualization Questions used in Study 1

Study 1							
ID	Visual stimulus	Projections	Object	Answer 1	Answers 2	Answer 3	Answer 4
1		Cube	315,0	360,0	3250,0	270,45	270,105
2		L shape	0,90	90,90	180,90	270,90	0,90
3		Cone 1	45,0	90,90	45,0	360,90	315,180
4		Pyramid	0,90	0,90	180,90	270,90	360,0
5		Box 2	0,45	0,120	135,150	45,135	0,45
6		L shape	270,90	180,90	0,90	270,90	90,90
7		Torus 1	180,135	180,135	90,105	180,30	90,150
8		Guitar	0,90	0,90	180,90	270,90	360,0
9		Box 2	135,45	135,45	210,45	45,45	315,45
10		L shape	0,0	180,0	0,0	180,180	0,180
11		Pyramid 2	270,90	270,90	315,180	240,0	90,90

Study 1							
ID	Visual stimulus	Projections	Object	Answer 1	Answers 2	Answer 3	Answer 4
12		Airplane	180,135	180,135	90,105	180,30	90,150
13		Teapot	210,0	210,0	120,0	300,0	30,0
14		L shape	180,120	270,120	180,120	0,120	90,120
15		L shape	15,90	15,90	15,45	15,0	165,0,
16		C shape 2	210,0	210,0	120,0	300,0	45,0
17		Sand clock	15,75	15,105	15,75	165,75	165,105
18		L shape	30,60	210,60	30,120	30,60	210,120
19		Tube	15,75	15,105	15,75	165,75	165,105
20		Chess horse	90,135	0,120	0,60	90,135	90,45
21		L shape 3	90,135	0,120	0,60	90,135	90,45
22		L shape	135,45	210,45	135,45	45,45	315,45
23		Chair	0,105	0,105	0,75	0,60	0,120
24		Prism 1	30,120	315,60	315,135	30,120	210,150

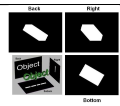
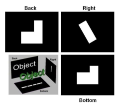
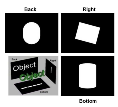
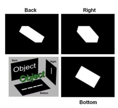
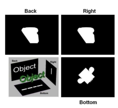
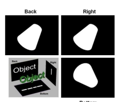
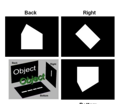
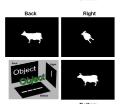
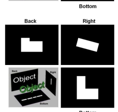
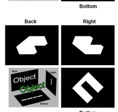
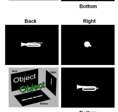
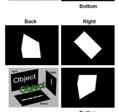
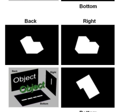
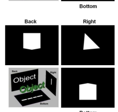
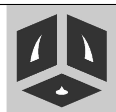
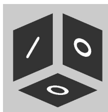
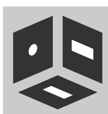
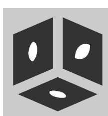
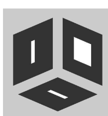
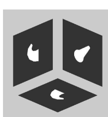
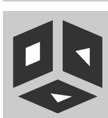
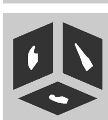
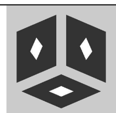
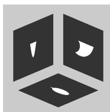
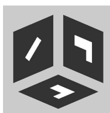
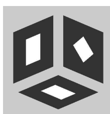
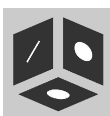
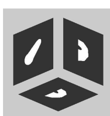
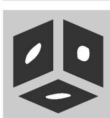
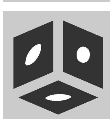
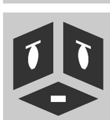
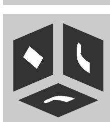
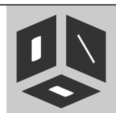
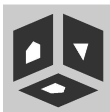
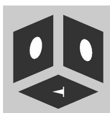
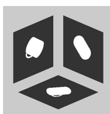
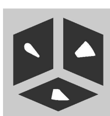
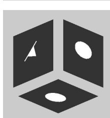
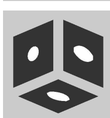
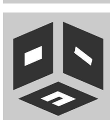
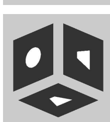
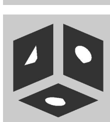
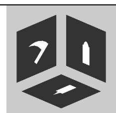
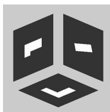
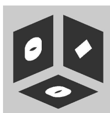
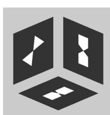
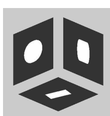
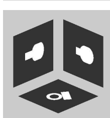
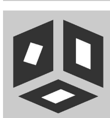
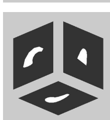
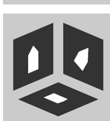
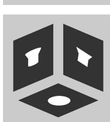
Study 1							
ID	Visual stimulus	Projections	Object	Answer 1	Answers 2	Answer 3	Answer 4
25		Soda bottle	60,30	150,15	60,15	60,30	150,30
26		L shape	0,60	0,105	0,75	0,60	0,120
27		Cylinder	0,105	0,105	0,75	0,60	0,120
28		Box	60,30	150,15	60,15	60,30	150,30
29		Phone	45,45	0,45	60,45	75,45	45,45
30		Cone 2	45,45	0,45	60,45	75,45	45,45
31		Prism 2	180,45	180,105	180,135	360,120	180,45
32		Cow	180,45	180,105	180,135	360,120	180,45
33		L shape	180,165	180,135	180,120	180,165	180,150
34		C shape 1	135,150	180,150	135,150	135,165	180,165
35		Trumpet	180,45	45,30	45,45	180,30	180,45
36		Prism 3	180,45	45,30	45,45	180,30	180,45
37		L shape 2	120,60	120,60	120,75	225,60	225,75
38		Pyramid 3	180,135	180,120	180,165	180,135	180,150

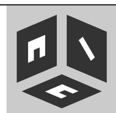
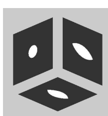
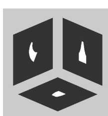
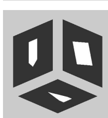
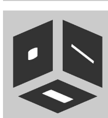
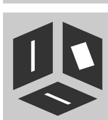
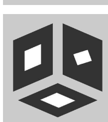
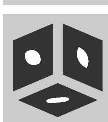
Table A.2: Visualization Questions used in Study 3

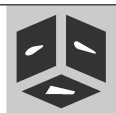
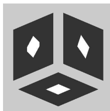
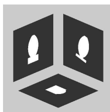
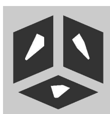
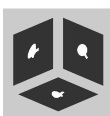
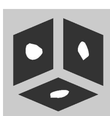
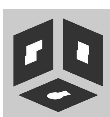
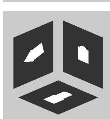
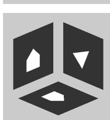
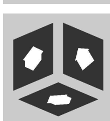
Study 3							
			X-, Y- and Z-axis rotation angles				
ID	Question	Frequency	Object	Answer 1	Answers 2	Answer 3	Answer 4
1		Once	0,45,0	0,45,0	0,135,0	180,45,0	180,135,0
2		Once	0,0,45	45,0,0	-45,0,0	0,0,-45	0,0,45
3		Once	-45,0,0	45,0,0	-45,0,0	135,0,0	-135,0,0
4		Repeated	90,0,0	90,0,0	0,90,0	0,0,90	30,0,0
5		Once	0,0,0	90,0,0	0,90,0	0,0,90	0,0,0
6		Once	45,0,0	45,0,0	-45,0,0	45,45,90	-45,45,0
7		Once	0,0,0	45,0,0	0,0,0	45,45,90	0,45,0
8		Once	45,0,90	45,0,0	-45,0,0	45,0,90	-45,0,90
9		Once	-90,0,0	90,0,0	-90,0,0	90,45,0	-90,45,0
10		Once	135,0,0	45,0,0	-45,0,0	135,0,0	-135,0,0
11		Repeated	45,0,0	45,0,0	-45,0,0	135,0,0	-135,0,0
12		Once	90,-45,0	90,45,0	90,-135,0	90,-45,0	90,135,0

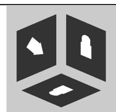
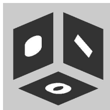
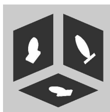
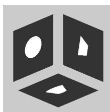
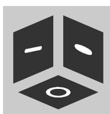
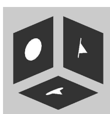
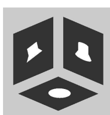
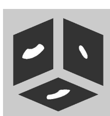
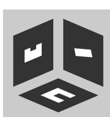
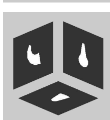
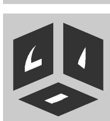
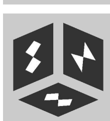
Study 3							
			X-, Y- and Z-axis rotation angles				
ID	Question	Frequency	Object	Answer 1	Answers 2	Answer 3	Answer 4
13		Once	0,90,0	0,90,45	0,90,0	90,45,90	90,0,90
14		Once	0,45,90	0,45,90	0,-135,90	0,-45,90	0,135,90
15		Once	90,-135,0	90,45,0	90,-45,0	90,135,0	90,-135,0
16		Once	45,0,0	0,45,0	0,0,0	45,-45,0	45,0,0
17		Once	0,0,45	45,0,0	-45,0,0	0,0,-45	0,0,45
18		Repeated	90,45,0	90,45,0	90,135,0	90,-45,0	90,-135,0
19		Once	45,0,-45	45,0,45	-45,0,-45	45,0,-45	-45,0,-45
20		Once	90,135,0	90,45,0	90,135,0	90,-45,0	90,-135,0
21		Repeated	45,0,135	45,0,45	-45,0,-45	45,0,135	-45,0,-135
22		Repeated	180,45,0	0,45,0	0,0,0	180,0,0	180,45,0
23		Once	0,90,135	0,90,45	0,90,-45	0,90,135	0,90,-135
24		Repeated	0,-135,0	0,-15,0	0,45,0	0,135,0	0,-135,0

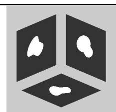
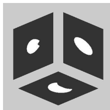
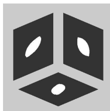
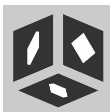
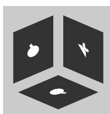
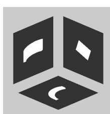
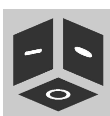
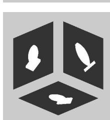
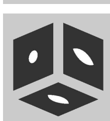
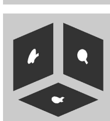
Study 3							
			X-, Y- and Z-axis rotation angles				
ID	Question	Frequency	Object	Answer 1	Answers 2	Answer 3	Answer 4
25		Once	45,0,90	45,0,0	-45,0,0	45,0,90	-45,0,90
26		Repeated	45,0,0	45,0,0	-45,0,0	135,0,0	-135,0,0
27		Once	90,180,135	90,0,45	90,0,-45	90,180,135	90,180,-135
28		Repeated	-45,0,-135	45,0,45	-45,0,-135	-45,0,-45	45,0,135
29		Once	0,45,45	0,45,45	0,45,-45	0,-45,45	0,-45,-45
30		Repeated	0,-45,-45	0,45,45	0,45,-45	0,-45,45	0,-45,-45
31		Once	0,0,-135	0,0,45	0,0,-45	0,0,135	0,0,-135
32		Once	90,0,0	0,30,90	90,0,0	45,0,45	0,0,0
33		Once	0,45,0	0,135,0	0,135,180	0,135,90	1,135,-90
34		Once	15,0,0	15,0,0	-15,0,0	45,0,0	-45,0,0
35		Repeated	90,90,180	0,90,0	90,90,180	0,180,90	0,90,180
36		Once	0,0,-135	0,0,45	0,0,-45	0,0,135	0,0,-135

Study 3							
ID	Stimulus	Frequency	Projections	Answer 1	Answers 2	Answer 3	Answer 4
37		Once	0,-180,45	0,90,45	180,45,0	0,45,0	0,-180,45
38		Repeated	75,0,0	75,0,0	110,0,0	45,0,0	15,0,0
39		Repeated	-45,0,0	15,0,0	-15,0,0	45,0,0	-45,0,0
40		Once	20,90,0	-20,90,0	20,0,0	20,90,0	-20,0,0
41		Once	0,0,-40	0,0,-10	0,0,40	0,0,-40	0,0,10
42		Repeated	90,0,15	90,0,15	90,0,-15	90,0,60	90,0,-60
43		Once	0,55,0	0,55,0	0,85,0	0,105,0	0,135,0
44		Once	0,0,60	0,0,45	0,0,90	0,0,60	0,45,0
45		Repeated	15,0,0	-15,0,0	0,15,0	0,90,0	15,0,0
46		Once	45,0,-45	-45,0,-45	-45,0,45	45,0,-45	45,0,45
47		Once	30,0,0	30,0,0	60,0,0	-60,0,0	-30,0,0
48		Once	10,0,0	10,0,0	-20,0,0	40,0,0	-50,0,0

Study 3							
			X-, Y- and Z-axis rotation angles				
ID	Question	Frequency	Object	Answer 1	Answers 2	Answer 3	Answer 4
49		Repeated	45,90,0	15,90,0	-15,90,0	45,90,0	-45,90,0
50		Once	0,0,15	0,0,75	0,0,195	0,0,15	0,0,255
51		Repeated	0,45,0	0,15,0	0,45,0	0,-15,0	0,-45,0
52		Repeated (Incr)	90,90,105	90,90,105	90,90,75	90,90,135	90,90,45
53		Repeated (Incr)	15,0,0	45,0,0	15,0,0	-15,0,0	-45,0,0
54		Once	90,60,0	90,120,0	90,90,0	90,60,0	90,30,0
55		Repeated	-15,0,0	-15,0,0	15,0,0	-15,90,0	15,90,0
56		Repeated	0,-15,90	0,45,90	0,15,90	0,-15,90	0,-45,90
57		Repeated	90,0,-20	90,0,10	90,0,-20	90,0,40	90,0,-60
58		Once	-30,0,0	30,0,0	10,0,0	-10,0,0	-30,0,0
59		Repeated	-30,0,90	30,0,90	10,0,90	-10,0,90	-30,0,90
60		Repeated	-30,0,45	60,0,45	30,0,45	-30,0,45	-60,0,45

Study 3							
			X-, Y- and Z-axis rotation angles				
ID	Question	Frequency	Object	Answer 1	Answers 2	Answer 3	Answer 4
61		Once	0,210,0	0,210,0	0,190,0	0,-190,0	0,-210,0
62		Once	-15,0,0	45,0,0	15,0,0	-15,0,0	-45,0,0
63		Once	15,0,0	45,0,0	-45,0,0	-15,0,0	15,0,0
64		Repeated	-45,90,45	45,90,45	-45,90,45	45,90,-45	-45,90,-45
65		Once	55,0,0	55,0,0	25,0,0	-25,0,0	-55,0,0
66		Repeated	-45,0,-135	45,0,45	-45,0,-135	-45,0,-45	45,0,135
67		Repeated	0,0,55	0,0,55	0,0,25	0,0,-25	0,0,-55
68		Once	90,0,105	90,0,15	90,0,105	0,90,195	0,-180,285
69		Once	0,-45,0	0,135,0	0,-135,0	0,45,0	0,-45,0
70		Repeated	0,0,105	0,0,15	0,0,105	0,90,195	0,-180,285
71		Repeated	45,0,0	-15,0,0	15,0,0	45,0,0	-45,0,0
72		Once	-45,45,0	-15,45,0	-15,0,0	-45,45,0	-45,0,0

Study 3							
			X-, Y- and Z-axis rotation angles				
ID	Question	Frequency	Object	Answer 1	Answers 2	Answer 3	Answer 4
73		Once	0,0,-135	0,0,45	0,0,-45	0,0,135	0,0,-135
74		Once	30,0,0	-30,0,0	-10,0,0	10,0,0	30,0,0
75		Once (Incr)	-45,45,0	-15,45,0	-15,0,0	-45,45,0	-45,0,0
76		Repeated 3	100,0,0	80,0,0	90,0,0	100,0,0	110,0,0
77		Once (Incr)	0,0,-10	0,0,-30	0,0,-10	0,0,10	0,0,30
78		Once	100,0,0	80,0,0	90,0,0	100,0,0	110,0,0
79		Once	0,90,195	0,180,-280	0,90,-195	0,90,195	0,180,285
80		Once	45,90,0	15,90,0	-15,90,0	45,90,0	-45,90,0
81		Once	-15,90,0	15,90,0	-115,90,0	45,90,0	-45,90,0
82		Once	30,0,0	30,0,0	60,0,0	-60,0,0	-30,0,0
83		Repeated	0,0,100	0,0,110	0,0,100	0,0,90	0,0,80
84		Once	15,0,0	-15,0,0	0,15,0	0,-15,0	15,0,0
85		Once	45,45,0	45,90,0	-45,90,0	45,45,0	-45,45,0

Study 3							
			X-, Y- and Z-axis rotation angles				
ID	Question	Frequency	Object	Answer 1	Answers 2	Answer 3	Answer 4
86		Once	-45,0,45	45,0,-45	45,0,45	-45,0,45	-45,0,-45
87		Once	15,0,0	15,0,0	-15,0,0	45,0,0	-45,0,0
88		Once (Incr)	-45,0,-45	45,0,-45	45,0,45	-45,0,-45	-45,0,45
89		Once	45,-30,0	45,10,0	45,-30,0	45,-10,0	45,30,0
90		Repeated	45,-45,0	45,-45,0	45,45,0	-45,-45,0	-45,45,0
91		Repeated	20,90,0	-20,90,0	20,0,0	20,90,0	-20,0,0
92		Once (Incr)	45,0,0	45,0,0	0,90,0	0,0,45	0,0,0
93		Once (Unstr)	0,0,-10	0,0,-10	0,0,-30	0,0,10	0,0,30
94		Once (Unstr)	45,0,0	-15,0,0	15,0,0	45,0,0	-45,0,0
95		Once (Unstr)	90,90,105	90,90,105	90,90,75	90,0,135	90,0,45
96		Once (Unstr)	-45,45,0	-15,45,0	-15,0,0	-45,45,0	-45,0,0
97		Repeated (Unstr)	15,0,0	45,0,0	15,0,0	-15,0,0	-45,0,0
98		Repeated (Incr)	-45,0,-135	45,0,45	-45,0,-135	-45,0,-45	45,0,135

Appendix B

Incremental and Unstructured Experiment Sessions

The following table presents the order in which visualization questions were shown in the Incremental and the Unstructured training treatments.

Table B.1: Characteristics of experiment sessions in the Incremental training

Session number	Total questions	ID of questions used
2	30	1,2,3,4,5,6,7,8,9,10, 11,12,13,14,15,16,17,18,19,20, 21,22,23,24,25,26,27,28,29,30
3	40	31,32,33,34,35,36,37,38,39,40, 41,42,43,38,44,45,46,47,48,49, 50,51,28,26,52,53,54,55,56,57, 58,59,60,61,62,63,64,65,66,67
4	40	68,69,24,42,28,70,71,72,45,51, 73,74,75,76,77,78,79,80,81,82, 83,84,85,52,86,56,59,87,88,89, 90,91,35,39,53,57,60,64,98,67
5	20	92,4,11,21,18,55,22,98,30,26, 38,49,57,53,83,90,64,70,76,91

Table B.2: Characteristics of experiment sessions in Unstructured training

Session number	Total questions	ID of questions used
2	30	93,24,49,64,28,32,45,94,85,40, 51,55,41,10,11,95,82,23,33,59, 91,54,26,42,70,96,81,38,56,43
3	40	50,39,57,90,73,97,72,83,17,60, 69,90,45,61,2,25,26,94,14,78, 67,76,89,30,64,22,4,12,66,21, 74,16,63,83,34,18,62,35,1,76
4	40	22,39,44,7,11,79,9,30,38,18, 37,47,80,46,55,84,28,4,20,26, 66,68,31,59,57,35,60,67,97,24, 13,19,91,42,48,52,21,36,58,64
5	20	49,57,28,53,56,27,86,66,51,29, 65,38,15,87,64,6,5,8,64,3

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Relevant Publications and Presentations

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• **Maria Velez**, Marilyn Tremaine, Aleksandra Sarcevic, Bogdan Dorohonceanu, Allan Krebs, and Ivan Marsic, *Who's in Charge Here?: Communicating Across Unequal Computer Platforms*, ACM Transactions on Human-Computer Interaction (TOCHI), Vol. 11 No. 4, 2004, 407-444.

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