COMBINING 2D AND 3D VIEWS FOR VISUALIZATION OF SPATIAL DATA

by

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B.Sc. University of British Columbia, 1999

THESIS SUBMITTED IN PARTIAL FULFILMENT OF
THE REQUIREMENTS OF THE DEGREE OF
DOCTOR OF PHILOSOPHY

in the
School of Computing Science

SIMON FRASER UNIVERSITY

July 2004

APPROVAL

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Date Approved: July 6th, 2004

Abstract

This research compares two-dimensional (2D), three-dimensional (3D), and 2D/3D combination displays (orientation icon, ExoVis, and in-place) for visualization of 3D spatial data. Both 2D and 3D views can be valuable for different reasons. 3D views can provide an overview of a 3D space, illustrate the 3D shape of objects, and support 3D navigation. 2D views can reduce occlusion of specific parts, show undistorted angles and distances, and enable precise positioning and navigation. Combining 2D and 3D views is valuable when benefits of 2D and 3D are both relevant to the task.

First, three 2D/3D combination displays were compared in terms of physical integration of views, occlusion, deformation, flexibility, screen space requirements, and viewing angles. Orientation icons (i.e., 2D and 3D views separated into different windows) offered high flexibility, non-oblique viewing, and low occlusion and deformation, but required substantial screen space and had poor integration of 2D and 3D views. In-place displays (i.e., clip and cutting planes) were the opposite. ExoVis displays (i.e., 2D views surrounding a 3D view in the same scene) had better integration than orientation icons, but greater flexibility and less occlusion and deformation than in-place displays.

A theory describing when orientation icon, ExoVis, and in-place displays would be useful was then developed, and experiments that compared 2D displays, 3D displays, and 2D/3D combinations for mental registration, relative positioning, orientation, and volume of interest tasks were performed. In-place supported the easiest mental registration of 2D and 3D views, followed by ExoVis, and lastly orientation icon displays. 3D displays were effective for approximate navigation and positioning when appropriate cues (e.g., shadows) were present, but were not effective for precise navigation and positioning except in specific circumstances (e.g., with good viewing angles). For precise tasks, orientation icon and ExoVis displays were better than 2D or 3D displays alone. These displays had as good or better performance, inspired higher confidence, and allowed natural, integrated navigation. In-place displays were not effective for 3D orientation because they forced users to frequently switch back and forth between dimensions. Major factors contributing to display preference and usability were task characteristics, personal strategy, orientation cues, spatial proximity of views that were used together, occlusion, oblique viewing of 2D views, and methods used to interact with the display. Results of this thesis can be used to guide designers to choose the most appropriate display technique for a given task.

for my husband Colin

without whom this wouldn't be written

and for Quentin

who changed the end

Acknowledgements

I would like to thank the Natural Sciences and Engineering Research Council (NSERC) and the Advanced Systems Institute (ASI) for funding my research. The Imager laboratory at the University of British Columbia generously loaned me the Polhemus input device used in experiment 2.

I would never have finished this thesis without the help of several people. Thanks to my husband, Colin, for convincing me to enter the field in the first place, and for endless conversations, reviews, and support. Thanks to my supervisor, Torsten Möller, for providing constructive criticism and always pushing me to think about things more deeply. Thanks also to the other members of my committee (Stella Atkins, Ted Kirkpatrick, and Lyn Bartram) for their many revisions of my work. Students in the GrUVi and Medical Imaging labs provided valuable feedback on my ideas; their friendship helped make my time at SFU interesting and enjoyable. Finally, thanks to my friends and family for their understanding and support.

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Chapter 1: Introduction

1 Background

1.1 Two- and Three-Dimensional Views in Visualization

Gaining insight from 3D spatial data sets (such as volume data or computer aided design (CAD) models) can be challenging because high data density makes it difficult to view all the data at once. For example, a typical medical scan might generate a volume with 512^3 voxels. Since our visual system cannot perceive objects occluded in depth, we must display the volume as a set of 512 two-dimensional (2D) slices if we want to see all details of the data set. However, slice-based views have several disadvantages. First, the third inherent spatial dimension of the data set is lost in the visualization, forcing the viewer to mentally reconstruct a three-dimensional (3D) model of the data. Furthermore, on a typical computer monitor, only a few slices could be viewed at once if the user wants to see reasonably sized images (e.g., radiologists typically prefer images to be postcard size or larger). Displaying volume data is even more challenging when the data is multivariate (has more than one dependent variable). For example, the amount of data in the medical example above could double if the patient had two types of medical scans (e.g., anatomical and functional scans).

Methods to visualize volume data in 3D have been extensively studied – primarily isosurface extraction [29] and direct volume rendering (DVR) [7][26][27][32][59][68]. These methods display the entire data set at once and successfully portray the 3D nature of the data set, but each voxel contributes only a small amount to the final image, so details are lacking.

Similarly, when viewing a CAD model, parts of the model near the front can occlude parts at the back, making it impossible to see all features of the model from a single viewpoint. For this reason, CAD models are usually displayed from several different viewpoints at once, typically from three standard orthogonal directions (2D "orthographic views") plus one or more oblique viewpoints (to give an impression of the model's 3D structure). In this case, the number of views may be smaller than in the medical example, but fitting these views onto a computer screen can still be difficult. More importantly, users must mentally relate and integrate information from the various views in order to understand and manipulate model geometry. These mental registration and integration tasks can be challenging and require cognitive resources [42]. Therefore, even when very large displays (e.g., wall displays) are available to fit all relevant views on the screen, it is important to consider the arrangement and integration of the various views.

Both 3D and 2D visualization strategies[1] have value for tasks involving 3D spatial data. Previous research has shown that each strategy is appropriate for different tasks. For example, Springmeyer et al. observed that 2D techniques are often used to establish precise relationships between parameters, whereas 3D views are typically used to gain a qualitative understanding of the data and present that understanding to others [50].

Since both 3D and 2D display strategies can be valuable for different reasons, it may be beneficial to integrate both 2D and 3D views into a single display. Surprisingly, although this approach is becoming fairly common, little experimental research to compare and evaluate different methods of combining 2D and 3D views has been done. This thesis addresses that gap in our collective knowledge.

1. A 2D view is defined here as a slice or front/back, right/left, or top/bottom view (e.g., an orthographic projection or line drawing showing object edges). 2D views provide information about only 2 spatial dimensions. A 3D view is defined as any other type of perspective or parallel projection. 3D representations provide information about 3D spatial structure. 3D views include, but are not limited to, stereo projections of objects.

1.2 Methods to Combine 2D and 3D Views

To combine 2D slices (cross-sections) with a 3D overview, three basic methods that are representative of the range of possible approaches are:

- ***Clip or cutting planes (also called in-place techniques)***: 2D slices are shown in their original location within the 3D view, so the slices are "in-place". Slices may not be translated, rotated, or scaled relative to the 3D view.
- ***Orientation icons***: 2D and 3D views are shown in separate areas of the screen (often in separate windows or viewports) and 2D views are always presented non-obliquely (i.e. flat on the screen). 2D views may be translated, scaled, and rotated relative to their original location in the 3D scene.
- ***ExoVis***: 2D views are shown in the same window as the 3D scene and may be translated and scaled, but not rotated, relative to the 3D view.

These methods are illustrated in Figure 1.1.

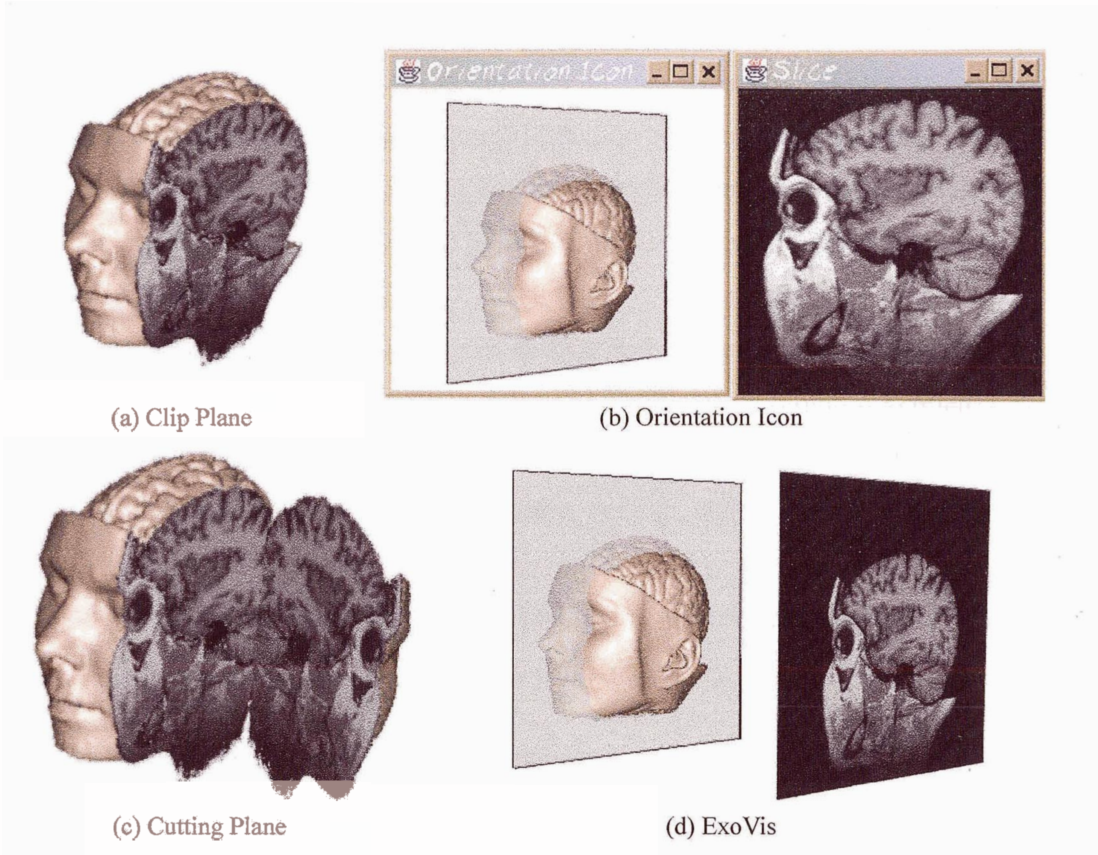

Figure 1.1: Methods to combine a 2D slice with a 3D isosurface.
(a) clip plane, (b) orientation icon, (c) cutting plane, and (d) ExoVis. Examples show a slice through a Magnetic Resonance Imaging (MRI) head scan.
Images are reprinted from [55], ©2003 IEEE.

1.2.1 Definitions of 2D/3D combination methods in terms of mental transformations

2D/3D combination techniques can be defined in terms of the mental transformations (i.e., mental rotation, scaling, and translation operations) required to mentally relate one 2D and one 3D view (a process also called mental registration). When people compare two scenes to determine if the scenes contain identical objects (that may be rotated, scaled, or translated relative to one another), they often transform one scene through mental imagery so they can compare it to the other scene at the same orientation, distance, and scale. For example, Mental rotation is a type of mental transformation in which a mental representation of an object is rotated through intermediate positions in a trajectory, as though the object were being rotated in physical space. Mental translation and scaling are analogous. Time required to perform mental rotation has been found to increase proportionally to the angle of disparity between the two scenes [47]. Later studies found that mental scaling [3][6] and translation [3] function similarly. These mental transformations are expected to play an important role in mental registration of 2D and 3D views, and mental rotation is expected to be the most cognitively demanding of the transformations.

2D/3D combination methods can now be defined as follows:

- ***In-place techniques***: no mental transformations are required to relate a 2D view to the 3D view.
- ***Orientation icon***: mental translation, scaling, and rotation may be required to relate a 2D view to the 3D view.
- ***ExoVis***: mental translation and scaling may be required to relate a 2D view to the 3D view, but mental rotation is not necessary.

1.2.2 Detailed description of 2D/3D combination methods

Clip planes show slice details in their exact position in the 3D view (i.e. the details are "in place"), but adding a plane automatically removes all data between the clip plane and the viewer (see Figure 1.1a). Thus, to show a slice deep within a volume, most of the 3D information would be removed from the image. A similar method that shows a cross-section of a volume "in place" is the "planar brush" [70]. Although the planar brush does not clip away 3D view information, the 3D view is limited to a simple outline. Another alternative to the clip plane is to open up a volume along a cutting plane, using a book, fan, or cutting metaphor [10][11][25][35], as illustrated in Figure 1.1c. Thus the 3D view information is not removed, but simply pushed aside.

ExoVis essentially does the reverse of the cutting plane: the 3D view remains in the centre of the display and slice details are shown in the surroundings (see Figures 1.1d and 1.2). Because the detail views are "outside" or "surrounding" the 3D overview of the world, these views are called "ExoVis" structures (from the Greek "exo-", meaning "outside", "outer", or "external"[2]). 2D ExoVis structures (e.g., Figures 1.1d and 1.2) show

2. *Webster's Encyclopedic Unabridged Dictionary of the English Language* (New York: Portland House, 1989), p. 500.

slices of the data and are called "walls". 3D ExoVis structures display subvolumes and are called "callouts". 3D callouts will not be discussed further because the thesis focuses on combining 2D views with a 3D overview, not 3D subvolumes. For details of 3D callouts, see [58].

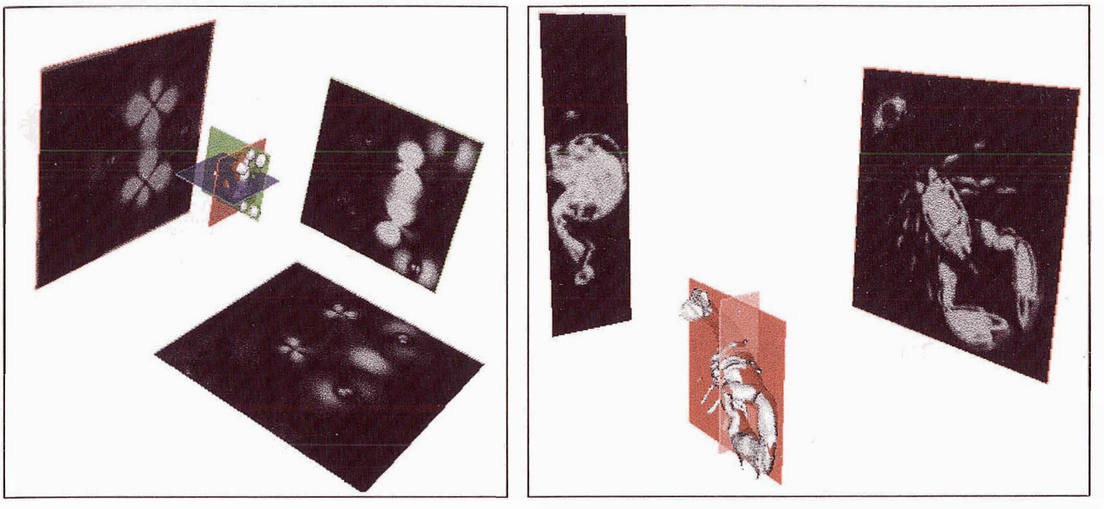

Figure 1.2: ExoVis examples.
ExoVis "walls" show slice details of a protein (left) and a lobster (right). Each wall shows a 2D slice of the 3D data set. Slice positions are indicated by coloured placeholders in the 3D view.

In the orientation icon approach, 3D and 2D views are shown in separate areas of the screen (Figure 1.1b). The 3D view acts as an "orientation icon", helping users to understand positions of the 2D views. Orientation icons are similar to ExoVis since both separate 2D views from the 3D view (i.e. the 2D details are "out of place"). However, ExoVis slices remain in their correct orientation relative to the 3D view (i.e. they are translated and possibly scaled from their original position), whereas orientation icon slices are potentially translated, scaled, and rotated from their original location; this allows slices to be viewed straight-on, but requires a mental rotation step to relate the 2D and 3D views (in addition to the mental translation and scaling that are required by both ExoVis and orientation icon methods).

For "out of place" techniques (orientation icons and ExoVis), "placeholders" within the 3D view indicate the positions and orientations of 2D slices. Placeholders are shown as semi-transparent grey planes in Figure 1.1 (b and d). Terminology and major differences between orientation icons and ExoVis are illustrated in Figure 1.3.

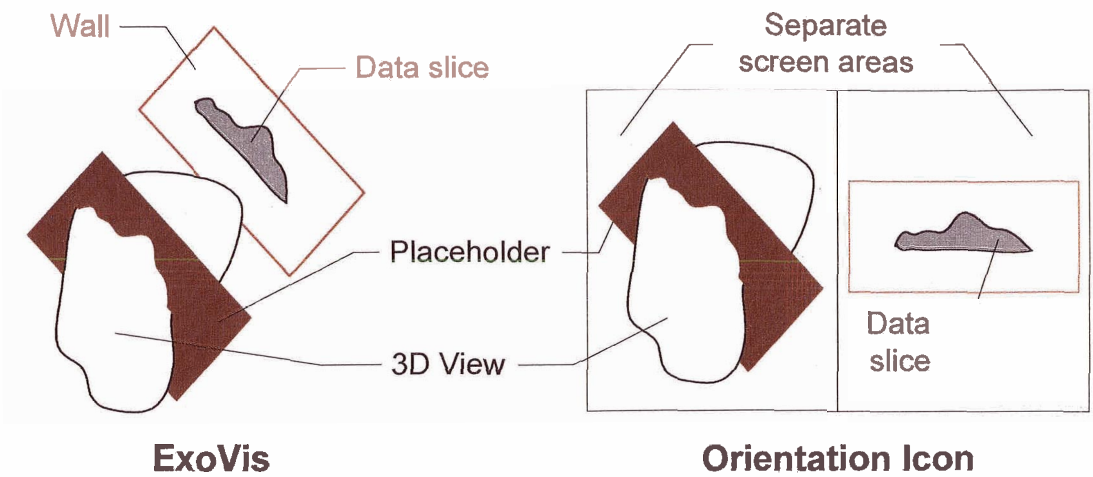

Figure 1.3: Out of place techniques: ExoVis and orientation icons.

Orthographic 2D views are different from slices since they are projections from outside the model. As such, they do not have positions within the 3D scene and the clip plane approach does not apply. Orthographic 2D views can be displayed using either the orientation icon or ExoVis methods. For the orientation icon method, placeholders may be used to indicate the position of view planes relative to the 3D view; however, placeholders are less important for orthographic views than for slice views since only the plane's orientation (not its depth) is important. Figure 1.4 illustrates the orientation icon and ExoVis methods of combining a 3D view with several 2D orthographic views.

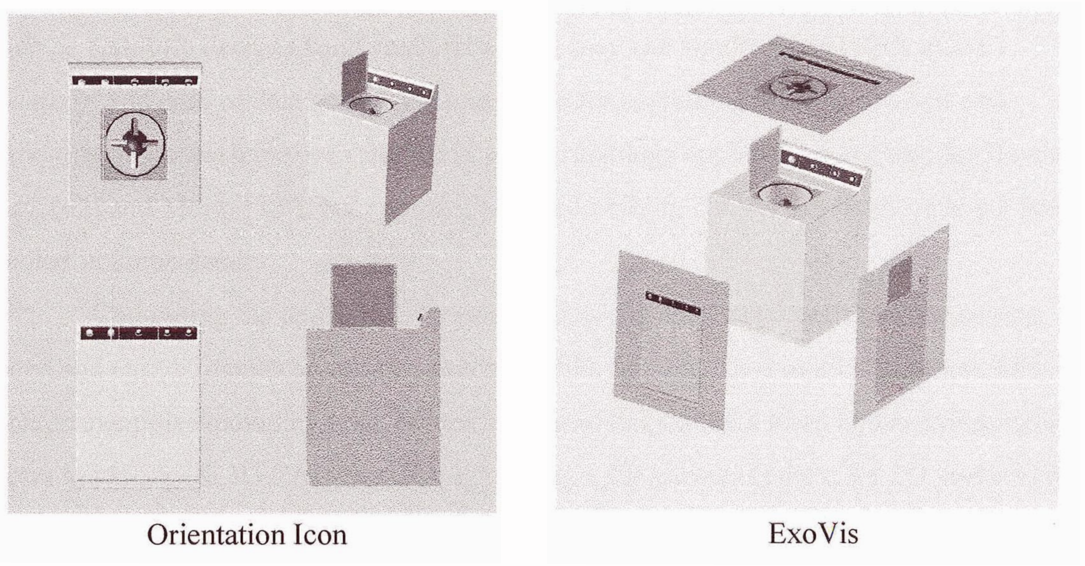

Figure 1.4: Orientation icon and ExoVis displays of a washing machine.
Images are reprinted from [55], ©2003 IEEE.

2 Thesis Summary

2.1 Problem Statement

The thesis compares several visualizations of 3D spatial data (e.g., volume data or CAD data) for common visualization subtasks. Specifically, it compares 2D or 3D views alone to three methods of combining a 3D view with one or more 2D views: (1) in place (clip and cutting planes), (2) orientation icons, and (3) ExoVis. The focus is on situations where the 3D view provides an overview of the scene and 2D views provide details. The goal is to determine the circumstances for which each 2D/3D combination method is appropriate.

2.2 Importance of the Study

3D spatial data is common in many different fields, but dense 3D structure can make analysis difficult. 2D (slice or orthographic view) strategies are common in many disciplines, and 3D approaches are now feasible and are becoming more commonly used and integrated with 2D approaches (e.g., [43],[60]). Presentation layouts and strategies must be carefully designed and studied because they can significantly affect speed, accuracy, and ease of data analysis. Approaches for presenting 2D views (slices and orthographic views) have been studied (e.g., for radiology applications see Van der Heyden *et al.* [62] and Moise [37]), but approaches for combining 2D and 3D views have not been studied in much detail.

Combining 2D and 3D views into a single display has potential for improving speed and ease of data analysis. For example, Pillay found that providing students with worked examples including both 2D and 3D views helped them learn to use orthographic views to work with 3D CAD models [42]. Using a 3D view as context for 2D views may be valuable: 2D views provide detailed information that may be necessary to perform some tasks, but a 3D view can help users understand the overall 3D structure of the data and the position and orientation of the slice or orthographic view. Providing this 3D context information may reduce the need for users to construct and remember 3D context information, and may therefore improve performance or make the task easier. Before we can make use of this idea, however, we need to learn when 3D context information aids and inhibits the task, and what characteristics of 3D context are most valuable in different situations. In a more general sense, we need to understand when having both 2D and 3D views is valuable, and how to best combine those views to support visualization tasks.

2.3 Delimitations

To clarify the scope of this research, this section describes some topics the thesis does not cover:

- The thesis is not a comprehensive comparison of all 3D data viewers. It focuses instead on characteristics of how 2D and 3D views are combined.
- The thesis does not focus on any application domain. Instead it considers tasks that are common to many domains, and draws examples and scenarios from several domains. Applying the general results of the thesis to specific applications is left to future work.

- The thesis does not evaluate all aspects of any visualization system. It focuses only on 2D and 3D display techniques.
- The thesis does not attempt to show that any method is fundamentally superior to all others. Instead, it identifies the circumstances for which each method is best suited.

2.4 Approach and Thesis Outline

The research process was divided into the stages outlined in Figure 1.5.

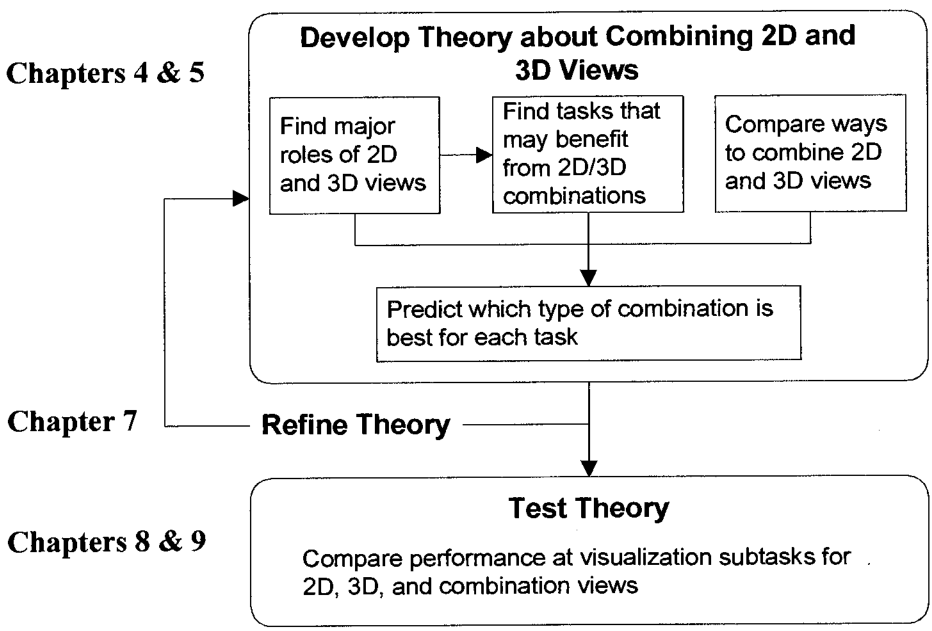

Figure 1.5: Outline of research approach.

A detailed outline of the steps to complete the thesis (and the relevant chapters) is below:

1. Summarize previous research on uses of 2D and 3D views and on combining 2D and 3D views. See chapter 2.
2. Select methodology that is appropriate for answering the thesis questions. See chapter 3.
3. Develop an initial theory about usage of 2D and 3D views:

   a. Perform a heuristic comparison of the 2D/3D visualization approaches to determine the advantages and disadvantages of each. See chapter 4.
   a. Based on a literature search, define major roles of 2D and 3D views, and determine what types of visualization subtasks may benefit from a combination of 2D and 3D views. See chapter 5.
   b. Hypothesize which type of 2D/3D view was most likely to be appropriate for each visualization subtask and why. See chapter 5.
4. Develop a set of experiments to test the remaining thesis questions. An overview of the experiments is given in chapter 6. Details are in the following chapters:
   a. Refine the theory from step 3 by testing an assumption about ease of mental registration. This assumption was empirically tested because it was based on theory rather than sound evidence from the literature. See chapter 7.
   b. Test the theory. For several visualization subtasks, performance, strategy, and perceived difficulty are compared with 2D views alone, 3D views alone, and several types of 2D/3D combinations. See chapters 8 and 9.
5. Discuss the experimental results (chapter 10), identify avenues for future work (chapter 11), and draw conclusions from the thesis (chapter 12).

Three appendices are included at the end of the thesis. Appendix 1 provides definitions for specialized terminology and acronyms used in the thesis. Appendix 2 includes detailed questionnaires used in the experiments in chapters 7-9. Appendix 3 provides complete statistical results from the three experiments.

2.5 Summary of Major Experimental Results

Mentally relating 2D and 3D views was most difficult with orientation icons, moderate with ExoVis, and easiest with in-place displays. However, this was not always the most important factor determining which type of display was best for higher-level tasks. Other factors influencing display preference and usability were task characteristics, personal strategy, spatial proximity of views that were used together, occlusion, oblique viewing of 2D views, and interaction techniques.

3D displays with appropriate cues (e.g., shadows) were effective for approximate navigation and relative positioning, but precise navigation and positioning were difficult with 3D displays. For precise tasks, orientation icon and ExoVis combination 2D/3D displays were better than 3D displays. In addition, compared to 2D displays, combination displays had as good or better performance, inspired higher confidence, and allowed more integrated navigation. Clip plane combination displays were not effective for 3D orientation because it was difficult to use more than one slice at a time and challenging to integrate information from several slices. Non-oblique 2D views (i.e., 2D views displayed flat on the screen, as in orientation icon displays) were useful for some precise judgments, whereas oblique 2D views (i.e., 2D views that were not rotated relative to their placeholders, as in ExoVis and clip plane displays) were better for understanding projections, relating the display to a 3D input device, and for rapidly switching attention between 3D and 2D views. Orientation icon displays may be preferred when the task has distinct 2D and 3D phases, and ExoVis may be preferred when 2D and 3D are used closely together.

Chapter 2: Related Work

1 What are the uses of 2D and 3D views?

3D computer graphics play a major role in visualization, especially for data sets that are inherently three-dimensional. Drawing 3D objects using 3D graphics makes sense intuitively - we live in a 3D world, so information presented in 3D should be easily processed [53]. However, the situation is not that simple. If 3D data is displayed as 2D slices or orthographic views, the third dimension alone is ambiguous. By contrast, 2D projections of 3D objects leave all dimensions somewhat ambiguous [49]. For example, perspective rendering causes distortion of angles and distances, producing challenges for precise positioning tasks. Furthermore, viewing 3D widgets on a small, flat, 2D computer screen, and interacting with them using a 2D mouse (or other input device), is far different from interacting with physical objects in our 3D world.

Several experiments have compared 3D displays to 2D displays for specific tasks, finding advantages for one or the other. Many of these experiments focus on aviation tasks (e.g., air traffic control and flight control). For example, Ellis and McGreevy compared pilots' collision avoidance strategies with perspective and orthographic view displays. They found that pilots made more vertical avoidance manoeuvres with perspective displays, resulting in a larger separation between the aircraft [13]. Similarly, Bemis *et al.* found that operators were faster and made fewer mistakes when detecting threats on perspective military tactical displays than on orthographic view displays [2]. In an air traffic control experiment, Van Orden and Broyles compared four tasks on several different displays. They found that 2D displays were as good or better than 3D displays for speed and altitude judgements, but 3D volumetric displays were best for collision avoidance tasks [63]. Similarly, Smallman et al. showed that visual search was faster with 2D air traffic control displays [49].

Comparisons of 2D and 3D displays have also been done outside the aviation domain. For precise positioning in telerobotic tasks, multiple 2D (orthographic view) displays have been reported superior to 3D monocular and stereo displays (in terms of number of errors and subjective user ratings). However, when visual enhancement cues were added to the scene (to partially compensate for depth ambiguity in the 3D displays), performance on 3D and 2D displays was equivalent [39].

These experiments have value for the specific domains and tasks studied, but it is hard to generalize from them to identify overall principles about when 2D and 3D views should be used. In addition to discussing different application domains and tasks, the experiments also vary greatly in terms of display parameters. For example, any of the following factors (based on Brown and Slater [5] and Smallman *et al.* [49]) might affect the ability of an operator to perform a task using a 3D display:

- Depth cues (perspective projection, stereo rendering, shadows, occlusion, shading, motion, etc.).
- Camera parameters (field of view, elevation, azimuth, etc.).
- Ability to manipulate the viewpoint.
- Exocentric ("through the window") or egocentric (immersion) display.
- Display hardware and input hardware.
- Information availability (i.e., whether important information is visible at all times or hidden until the user requests it).
- Additional enhancements (e.g., drop lines to indicate height).

Fortunately, a few research studies have attempted to elucidate more general principles about 3D and 2D displays. The "Proximity Compatibility Principle" (PCP) suggests that tasks requiring integration of spatial dimensions (i.e. 3D knowledge) will benefit from 3D displays, whereas tasks requiring focused attention on one or two dimensions will benefit from 2D displays [16]. In an experimental study, Haskell and Wickens confirmed these ideas for airplane cockpit displays [16]. They found that 3D displays improved flight control accuracy (except when there was a disturbance event during flight), but 2D displays were better for controlling airspeed (a task not integrated with other flight control tasks). In a related study with abstract economic data, Wickens *et. al.* determined that 3D (perspective) representations were better than 2D representations only for more integrative questions that required knowledge of several dimensions [69].

However, not all experimental evidence agrees with the PCP. St. John *et al.* [51] claim that usefulness of 2D and 3D views depends on more than simply the level of spatial integration required by the task. They showed that 3D displays were better than 2D displays for shape understanding tasks, whereas 2D displays were superior for relative positioning tasks, even when the positioning tasks required integrated 3D knowledge. The PCP would have predicted that 3D displays would be superior for both of these tasks since both require integrated 3D knowledge. In a related experiment, St. John *et al.* compared (1) 3D views, (2) 2D views, and (3) a side-by-side combination of 2D and 3D views for a 3D route planning task [52]. Time to complete the task was fastest with the side-by-side display and slowest with the 3D display, indicating that combinations of 2D and 3D views are valuable. The authors report that with the side-by-side display, participants used the 3D display at the start of the problem but then concentrated on the 2D display. Participants reported that the 3D views were useful for interpreting the 2D views. Hence it seems that 3D views are useful for gaining an overall impression of a 3D shape or 3D space and for understanding the orientation of 2D views. By contrast, 2D views seem more appropriate for precise positioning tasks.

The precise positioning hypothesis may also explain results of a study by Hollands *et al.* In their experiment, participants determined whether two vehicles were converging or diverging over time (a task requiring integration of x, y, and time dimensions) [18]. The PCP predicts that 3D displays would be superior to 2D displays since the task requires information integration. However, results showed that response accuracy was higher with 2D displays than with either monocular or stereo 3D displays for medium to high rates of convergence/divergence. It is possible that participants had to perform relative position judgements to determine whether the vehicles were converging, and that depth ambiguity could inhibit these judgements.

In general, although users often prefer 3D displays [49], 3D displays are not always good for them. Overall, the literature indicates that 3D and 2D displays are useful for different tasks. Table 2.1 summarizes these uses.

Table 2.1: Uses of 2D and 3D Views

3D views are valuable for...	*2D views are valuable for...*
Gaining an overview and orientation information (general layout of an information space, positions of 2D views, etc.).	Tasks that require information from only 1 or 2 dimensions at a time.
Understanding 3D shape.	Precise positioning and navigation, even when they require integration of all 3 dimensions.
Approximate 3D positioning and navigation.	Tasks involving a dense information space (i.e. when there is a lot of occlusion in the 3D views). 2D (slice) views eliminate occlusion for a specific region of interest.

Note that in some cases, adding enhancement cues to 3D displays can partially compensate for depth ambiguity and make them useful for tasks that would otherwise benefit from 2D displays. Similarly, highly trained individuals (e.g., CAD technicians or radiologists) can often work quite effectively with 2D displays alone by mentally visualizing the 3D scene. Cine mode is a mechanism that helps radiologists form this mental picture by allowing them to scan rapidly back and forth through a series of slices.

2 How should we combine multiple views?

Combining 2D and 3D views is a special case of combining multiple views. Hence, learning what is known about combining multiple views may help us combine 2D and 3D views more effectively.

Displaying multiple views of a data set can help users analyze data in a number of ways. For example, multiple views can [1]:

- Reduce clutter that would be present in a single display, and partition data into manageable chunks.
- Help users compare different components or representations of the data (e.g., different attributes, models, display styles, or levels of abstraction).

- Allow users to see details while still keeping track of their overall position (detail and context displays).

However, multiple view systems also have disadvantages, primarily the need for context switching. Switching attention between different views requires cognitive effort and time for reorientation [1]. In other words, mental effort is required to place a new scene into the context of previous scenes and the data as a whole [71], and to integrate information from several different views. In addition, extra views generally require extra screen space.

Difficulty of context switching and integrating data from multiple views depends on properties of the views themselves. Woods defines "visual momentum" as a measure of this difficulty [71]. When visual momentum is high, there is a continuity between the views that makes transitions between them easy. When visual momentum is low, switching between views requires significant mental effort. Properties that can increase visual momentum and decrease orientation difficulty include [1][71]:

- Consistent formatting and data organization across different views.
- Consistent interaction techniques across different views.
- Perceptual landmarks: easily discernable features that users can identify in each view to aid orientation.
- A global overview. An overview can help users understand positions of other views (particularly views of small subsets of the data) and can reduce the need to construct and remember a model of the data structure.
- Overlap between displays that illustrate relationships between the displays. For example, in "focus + context" displays, an area of interest is magnified relative to the remainder of the data set [9][45]. Between these two regions is a transition region with a continuous fall-off in magnification. This overlap area helps users orient the views relative to one another. Similarly, for two different viewpoints of a 3D scene, displaying additional intermediate stages between the two viewpoints can help people understand their spatial relationship [42].
- Navigational slaving: movements in one view automatically propagate to other views.
- Linking: views are connected in some way. Examples include:

  - Connecting lines between views (e.g., common in overview and detail displays).
  - Consistent colouring of objects. A specific type of colour linking is brushing: the user highlights a set of objects in one view and the system automatically highlights the same objects in other views.
  - Markers indicating positions of other views. For example, in overview and detail displays, the position of a detail view is usually indicated by a square (or other marker) in the overview display. Similarly, medical imaging displays typically include three orthogonal slices of the data (axial, coronal, and saggital). Within each view, two lines are drawn to indicate the current slice position for the other orientations.
- Physical placement of the views relative to each other for spatially related views. Closer spatial integration of views may reduce the mental effort required to understand their spatial relationship. For example, "focus + context" displays, in which a detail view is spatially located within a global overview, may have higher visual momentum than "overview + detail" displays, in which detail views and overviews are shown in separate windows [8, p. 634].

Most of these ideas are common to all multiple view systems and can be directly applied to 2D/3D displays. However, physical placement of the views relative to one another requires study. Methods of physically organizing 2D and 3D views in a combination display have not been analyzed or compared. This thesis addresses the physical organization issue.

3 How can 2D and 3D views be combined perceptibly?

3.1 How can we clearly identify positions of the placeholders?

For "out of place" techniques (orientation icons and ExoVis), placeholders are needed within the 3D view to indicate the positions and orientations of currently displayed slices. (Note: placeholders are not so important with 2D orthographic views.) Examples of placeholders were shown in Figures 1.1 and 1.3. How should these placeholders and the 3D view be rendered to make the positions most clear?

Experimentation with several different ways of rendering placeholders (wireframe, solid, semi-transparent, etc.) can begin to answer these questions. When the 3D object is opaque (e.g, an isosurface created from volume data), the position of a wall placeholder is most clear when the placeholder has an opacity approximately between 0.4 and 0.75, as shown in Figure 2.1. Similar mid-range opacities have been used for semi-transparent objects in other systems. For example, the "Silk Cursor" uses opacities of 0.38 and 0.6 [72]. (Note that the silk cursor opacities are slightly lower. This is because the cursor had a cube shape and the developers wanted the front and back walls of the cube to sum to approximately opacity 1.0 so that the cursor would almost occlude objects behind it but only partially occlude objects within it.)

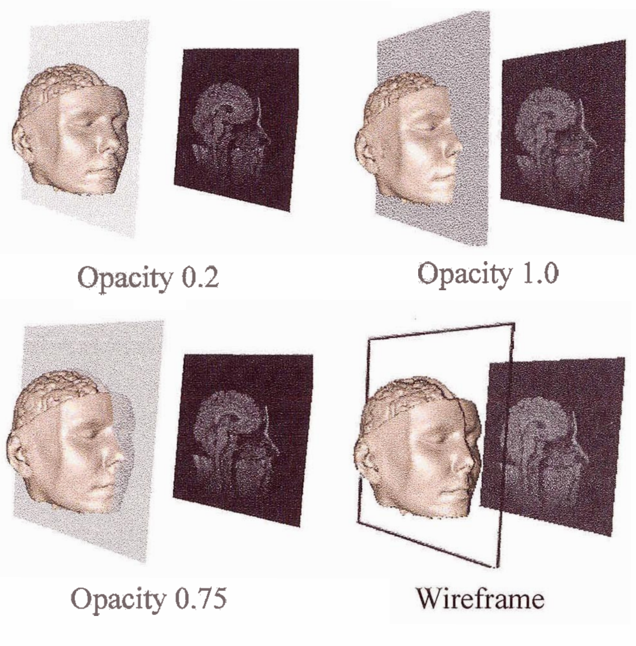

Figure 2.1: 2D placeholder rendering styles with opaque graphics.
Placeholders with opacity 0.75 (bottom left) show slice position without blocking the surface. Wireframe placeholders (bottom right) are less effective.

When the 3D object is semi-transparent (e.g., with direct volume rendering), wall position is most clear with an opaque placeholder. Notice the red placeholder around the lobster in Figure 2.2. When placeholders are wireframe (bottom left image) or semi-transparent (top left image), position of the placeholder relative to the lobster is unclear. With an opaque placeholder (top right), it is obvious that the placeholder is behind the lobster's front legs and in front of the lobster's tail (yellow arrows in Figure 2.2). Perception of the placeholder position can also be enhanced by adding an outline around the 3D object (see the yellow outline in the bottom right image of Figure 2.2).

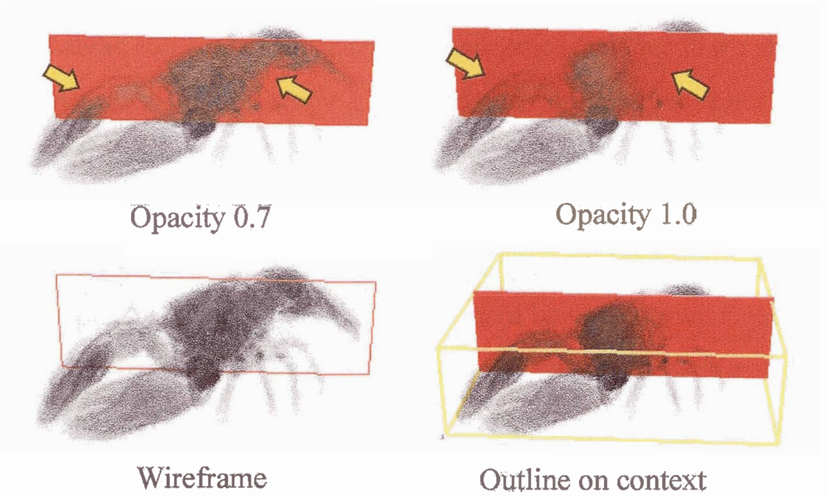

Figure 2.2: 2D placeholder rendering styles with a semi-transparent lobster. Placeholder position is best shown with opacity 1.0 (top right). Yellow arrows indicate areas that are ambiguous for semi-transparent placeholders (top left). An outline on the 3D overview is also helpful (bottom right).

In general, displaying a 2D placeholder as a filled rectangle is very important. Placeholders drawn as wire frames provide insufficient information for understanding their positions, as shown in Figures 2.1 and 2.2. Position of wireframe placeholders is clearer if a silhouette edge is added around the global context object where the plane intersects it (see the black line along the face in the wireframe image of Figure 2.1), but this is likely only effective for opaque objects.

Experience with the ExoVis prototype also demonstrated that placeholder colour must be carefully chosen. Darkly coloured placeholders can block large parts of the 3D object, especially when it is volume rendered. Negative interactions become even more complicated when a colour transfer function[1] is used for the 3D view. Using light colours for the placeholders helps to alleviate this problem.

Furthermore, placeholder colours must be clearly distinguishable from one another. Researchers disagree about exactly how many colours can be easily distinguished, with estimates ranging from 5 to 30 [61, p. 81][66, p. 135] for viewers with no colour vision deficiencies. Most agree, however, that the number of colours that can be used is small. Ware suggests using the following set of twelve: {red, green, yellow, blue, black, white, pink, cyan, grey, orange, brown, and purple}, with preference for the first six. His justification is that the colours are far apart in colour space and map to the most commonly named colours in a cross-cultural study. Colour blindness is another important consideration when choosing colours. Red-green colour blindness is the most common, so combinations of red and green should be avoided.

According to Healey [17], three criteria are important in choosing colours for pre-attentive visual search: 1) Colours should be separated by a maximum Euclidean distance in a perceptually balanced colour model. 2) Colours in a display should not be in the same named colour category. (People classify colours into common named categories. For example, most people might name colours ranging from yellow-green to blue-green as "green".) 3) Linear separation should be possible in the CIE LUV colour space. Healey found that obeying these rules produced colour sets in which visual search was pre-attentive. However, the largest set he could find to satisfy these criteria was seven colours. His results showed that visual search was easy with up to five colours, but more difficult for 7-9 colours, probably because some colour categories were duplicated.

Even if colours and transparencies of the placeholders and 3D object are carefully selected, there is a limit to the number of layers people can see. With several placeholders and possibly also several layers of information in the 3D object, this limit could be exceeded. Furthermore, if semi-transparent surfaces are used for the 3D object, perception of surface shape could be difficult. To aid user's ability to distinguish multiple surfaces and to perceive surface shape, textures on the objects can be used [21].

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1. A transfer function takes a set of input data values and maps them to a set of colours and opacities.

3.2 When should 2D views be displayed at oblique angles?

With clip planes and ExoVis, 2D views are displayed in their original orientations so that they are not rotated relative to the 3D view. For this reason, the 2D views will often be viewed obliquely (i.e. not straight on). Will this make information in the 2D views more difficult to perceive or interpret?

An object viewed from different angles produces different shapes on the retina, but can often be perceived as the same. For example, doors usually appear rectangular, even though they are rarely viewed straight-on. This perceptual phenomenon is called "shape constancy" [64].

Shape constancy implies that viewing images obliquely (as with clip planes and ExoVis) should be possible. Nonetheless, research indicates that perception of images viewed at an angle is not perfect. Rosinski and Farber suggest that "observers cannot judge that a scene is distorted unless they know what it is supposed to look like. This information is not available at the incorrect viewing point" [44]. For example, in a study where participants had to determine whether line drawings of boxes were rectangular, performance degraded when the pictures were viewed obliquely [41]. Similarly, Thouless showed that people perceive a circle shown at an angle as an ellipse [54]. This implies that perception of shape (especially judging whether lines are parallel) in 2D views could be slightly impaired with the "in place" and ExoVis techniques.

Furthermore, certain depth judgements are more difficult when images are viewed obliquely. Specifically, although spatial layout of a scene does not change, perceived orientation of objects in the scene relative to the observer varies greatly depending on the viewing angle [14]. In other words, changing the viewing angle does not change perceived positions of objects relative to one another, but does affect the perceived orientation of objects. This effect is greater for orientations close to perpendicular to the picture plane than for orientations close to parallel to the view plane [14]. (E.g., in some portraits, the eyes appear to follow observers as they move around the picture to view it from different angles. This effect is greatest when the participant's gaze points directly out of the picture plane.) This implies that performance at judging orientation of objects in 2D views may degrade when the 2D views are shown obliquely.

Chapter 3: Methodology

Before we can compare and evaluate different ways of combining 2D and 3D views, we must decide what methodology is appropriate.

1 Experiment Methodology Overview and Examples

Both functionality and ease of interaction for visualization systems can be tested. Several methods of evaluation are possible, but user studies are the most common. User studies involve real users in the testing process, and allow designers to obtain both qualitative and quantitative data to evaluate the system. Quantitative data typically measures task performance: either (1) time to complete a specific task or (2) accuracy (e.g., number of mistakes) while completing the task. User ratings on questions such as task difficulty or enjoyment also provide quantitative data, though the measures are subjective rather than objective. Qualitative data may be obtained through questionnaires, interviews, contextual inquiry, and/or observation.

Quantitative studies are by far the most common and accepted form of user testing in visualization. Few formal published studies are purely qualitative; most studies with qualitative results also include a quantitative component. For example, a study could measure time or accuracy in addition to obtaining qualitative results, or could quantify qualitative statements using ratings such as Likert scales. In a typical study, test conditions (e.g., display type) are identified and subjects are asked to perform specific tasks under each condition. Both between-subjects and within-subjects designs are common. Measures such as time to complete the task and number of mistakes are tracked and compared for the various conditions. Some user studies involve artificial or abstract data sets and controlled settings (for greater control over the experiment, higher internal validity, and relevance to many domains), while others involve realistic data sets and field settings (for greater realism and higher external validity). Examples of quantitative experimental methods include: [18][49] (artificial or abstract data sets), [2][52][63][69] (realistic data sets), and [51] (both real and artificial data sets). An example of a more qualitative study is [28], where verbal protocol analysis and questionnaires were used to gain information about group dynamics and decision making.

Additional evaluation methods established in human computer interaction include cognitive walk-throughs (where an expert "walks through" a specific task using a prototype system, thinking carefully about potential problems that could occur at each step) and heuristic evaluations (where an expert evaluates an interface with respect to several pre-defined heuristic criteria) [31]. Similarly, Blackwell et al. developed "cognitive dimensions", a set of heuristic criteria for evaluating cognitive aspects of a system [4], and Baldonado et al. designed a set of heuristic guidelines specific to multiple view visualizations [1].

2 Experiment Design Challenges

User studies can be time consuming, expensive, and difficult to design. Although they quickly highlight problems in an interface (e.g., it is quite obvious from observation if a user cannot find the appropriate button to perform a task), user studies do not always effectively find problems and benefits of visualization ideas. Benefits of the tool may be useful only to experts in the field (who can be difficult to find or may not have time to participate in lengthy studies) or following a long practice period. Results of a comparison of two tools may be confounded by the many differences between the two tools or by participants' previous experience with one or both tools. Missing or inappropriate features in the test tool or problems in the interface can easily dominate the results and hide benefits of the ideas we really want to test. Thus it seems that user studies can only be useful with an extremely polished tool, so polished that huge amounts of time and resources must be invested to test simple ideas that may in the end turn out to be worthless [65, Chapter 2].

Solutions to the above problem include:

- Focusing on design ideas rather than complete visualization tools.
- Testing specific hypotheses.
- Allowing a long practice period for complex tasks. For example, Park et al. had subjects practice a telerobotic tasks for several hours prior to experimental testing [39].
- Running a long-term study. For example, McGrenere added a custom plug-in to Microsoft Word and asked subjects to use it for their ordinary word processing tasks over a period of several weeks [34].

We should first use perceptual and cognitive theories to develop a design idea that is predicted to have a specific benefit. For example, we might predict that ordering data values by time will improve speed and reduce cognitive load for a task involving finding trends in the data over time. This translates easily into a hypothesis that can be tested. We can then develop a simple tool designed to test only this hypothesis. Our test should attempt to validate the hypothesis that the idea is effective, as well as the hypothesis stating why it is effective. Of course, this may not be as easy as it sounds. Taking the idea completely out of context may render it useless, or may limit our ability to generalize the results. Moreover, choosing an appropriate level of tool complexity may be a difficult decision involving many trade-offs.

Usability inspection methods avoid many of the problems with user studies and may be beneficial for evaluating visualizations. However, because these techniques are (for the most part) designed for user interface testing and focus on production products rather than the underlying concepts, it is not clear how well they will evaluate visualization ideas. For example, many visualization tasks are ill-defined. Walking through a complex cognitive task is very different from walking through a well-defined interface manipulation task. Furthermore, by leaving end users out of the evaluation process, usability inspection methods limit our ability to find unexpected errors.

3 Methods Used in this Thesis

3.1 User Study Methods

This thesis used fairly standard quantitative user study methods (i.e., timing, accuracy, and subjective Likert scale measures) and a few qualitative methods (questionnaires, interviews, structured observation, and contextual inquiry). Major problems mentioned above were avoided by developing theoretical ideas to ground the study (see chapter 5), and by testing hypotheses underlying the theory or predicted by the theory. User studies were designed specifically to test these hypotheses, and did not attempt to test all aspects of a visualization system. Rather than testing complicated, domain-specific tasks, generalized visualization subtasks were used. These subtasks were selected through a triangulation process (i.e. by examining three different applications and finding tasks that were common to these areas); thus, the tasks should be relevant to many fields. Using generic tasks also reduces the need for domain-specific knowledge (so that non-experts could participate in the experiments). The selected visualization subtasks were also fairly simple, so a short practice period was expected to be sufficient.

The major drawback of this approach is that the results may not be exactly identical in particular domains. Further studies may be necessary to validate the results for specific tasks and users in field settings, especially when the task is mission-critical (e.g., flight control) or user time is expensive (e.g., radiology). However, performing such studies for every possible task, user, and application domain is highly unrealistic. Hence, results of generalized studies should be valuable for the large percentage of cases where the time and cost needed to run a specific study is unwarranted.

3.2 Statistical Analysis

Data was analyzed using classic statistical techniques. For a comprehensive background on these methods, see Huck [20] or another statistical text.

When assumptions of parametric methods were met, quantitative (interval) data such as timing and error data was studied using t-tests, for comparing two conditions, or analysis of variance (ANOVA), for comparing more than two conditions. When Mauchly's test of sphericity indicated it was necessary, the Huynh-Feldt correction was used in repeated measures ANOVA analyses. Significant effects identified in ANOVA were further investigated by pairwise comparisons (for within-subjects' variables) or Tukey Honestly Significant Difference (HSD) tests (for between-subjects' variables) to determine exactly which pairs of conditions were significantly different.

Nonparametric tests were also employed. Mann-Whitney U tests and Kruskal-Wallis H tests were used for between-subjects' variables. Friedman tests and Wilcoxon matched-pairs signed-ranks tests were used for within-subjects' variables. These nonparametric tests were used in the following circumstances:

- ***Rating scale data.*** Data from subjective rating scales (e.g., 1 = strongly disagree, 5 = strongly agree, etc.) do not necessarily reach an interval level of measurement because the distance between response options on the questionnaire may not exactly correspond to participant's opinions of how different the conditions are. Thus, rating scale data was considered ordinal rather than interval in nature, such that parametric techniques were not valid.
- ***Skewed data.*** Parametric techniques assume data is distributed approximately along a normal curve. When the data did not fit a normal curve, even when transformed, nonparametric methods were used.
- ***Small or uneven sample sizes.*** Because nonparametric techniques are more robust than parametric methods with very small or uneven sample sizes, they were used in these situations.

Chapter 4: Comparison of 2D/3D Combination Methods

Section 1.2 provided an overview of the major techniques to combine 2D and 3D views, specifically clip/cutting planes, orientation icons, and a new method called ExoVis. In this chapter, the techniques are described in more detail. They are then compared heuristically to determine their advantages and disadvantages.

1 Description of the Techniques

Clip and cutting planes slice directly through a 3D space to show 2D views "in place" (i.e., 2D slices are not moved from their original positions). This requires either removing or pushing aside information in the 3D view. By contrast, orientation icons show 2D and 3D views in separate areas of the screen, so the 2D views are "out of place". This allows 2D views to be rotated relative to the 3D view so they are not viewed obliquely. ExoVis is a new "out of place" technique. Examples of ExoVis were given in Figure 1.2 (see chapter 1). ExoVis is similar to the orientation icon, but 2D views are shown in the same screen area as the 3D view and may be translated and/or scaled, but not rotated from their original positions. Because of this, 2D views in ExoVis are often viewed obliquely.

Major differences between clip/cutting planes, ExoVis, and orientation icons were illustrated in Figure 1.1 (see chapter 1). Notice that for 2D orthographic views (where the 3D world is projected onto a 2D plane from a standard viewing position), the 2D view does not represent a "cut" through the 3D world. As such, clip and cutting planes apply only to slice views, not orthographic views.

1.1 2D/3D Methods for Detail and Context

Because many data sets are large and dense, it can be difficult or impossible to view all the data at one time. However, viewing the data in small subsections makes it difficult to keep track of the bigger picture. Hence, a major research theme in visualization is developing ways to show both an overview (also called context) and details (also called focus) simultaneously. With detail-and-context visualization tools, it is possible for users to look at details for an area of interest without forgetting where they fit in globally. Detail and context techniques exist for a wide variety of data types, and will not be reviewed in detail here. For an introduction, see [8] or [66].

Two major classes of detail-and-context techniques have been defined. *Overview + detail* techniques show both a global overview and details of a selected area, but in separate windows. An icon (typically a box) in the global view indicates the location of the details currently shown in the detail view [8, p. 634]. For some users and applications, integrating the two views in overview + detail displays may impose a cognitive overhead. For this reason, *focus + context* (also known as *detail-in-context*) methods were developed to keep the focus view spatially located within the global overview or context. This increases continuity between the global and local representations. A common example of a "focus + context" technique is the fish-eye lens. Fish-eye lens techniques are based on fish-eye camera lenses, which greatly magnify objects at the centre of the field of view, with a continuous fall-off in magnification towards the edges.

All three 2D/3D combination methods support detail and context. Specifically, they show 2D slice or orthographic view details along with their 3D context, so that users can easily understand positions and orientations of the 2D views. Clip and cutting planes are "focus + context" methods because the 2D details remain spatially located within the 3D context. By contrast, the orientation icon method is an "overview + detail" technique since the 2D and 3D views are spatially separated. ExoVis lies somewhere between these two extremes, but is closest to the overview + detail methods since the 2D views are displaced from their original locations. Major differences between the three techniques with respect to their ability to display detail and context relate to:

- Occlusion of 3D or 2D views by other views or placeholders,
- Deformation of the 3D or other 2D views by the 2D views,
- Ability to selectively magnify individual 2D views, and
- Ease of mentally registering the 2D and 3D views. Ideally this task should be very easy so that users can easily understand positions of 2D views.

For example, clip planes remove all data between the plane and the viewer, so occlusion of the 3D overview is very high. As the overview becomes more occluded, its usefulness is reduced. Similarly, cutting planes deform (cut through and separate) both the 3D overview and other 2D cutting planes. Such breaks may make visualizations more difficult to interpret. (E.g., colour perception can be affected by a break in an image, as illustrated by the Koffka Ring phenomenon [24].) Clip and cutting planes also cannot be magnified relative to the 3D view because they must remain "in place". However, clip and cutting planes have the advantage that mental registration of different views is very easy (since the views are not spatially separated).

With ExoVis, mental registration of 2D and 3D views should be easier than with orientation icons since mental rotation, or some other matching strategy, is not necessary to register the two views. Mental rotation is a type of transformation in which a mental representation of an object is rotated through intermediate positions in a trajectory, as though the object were being rotated in physical space. Time required to perform mental rotation increases as the angle of rotation increases [47]. Mental rotation has been suggested as a common strategy for understanding the relationship between various 2D and 3D views of objects in CAD diagrams [42]. Notice that for both orientation icons and ExoVis, slices can be translated and / or scaled from their original positions. Thus, mental translation and / or mental scaling operations (which are analogous to mental rotation) may be required to register the 2D and 3D views. Time to perform these mental operations also increases with the translation distance and scaling factor [3][6]. This implies that mental registration could be more difficult with an ExoVis display where the 2D view is displayed very far away from the 3D view or at a very different scale, as compared to an orientation icon display where the 2D and 3D views are close together and have a similar scale. However, when these two factors are similar for the two types of displays, mental registration should be easier with ExoVis since no mental rotation is required.

A more thorough comparison of the three techniques with respect to these criteria is given in section 2 of this chapter.

1.2 2D/3D Techniques for Relationship and History Tasks

Another research theme asks how to design visualization tools to support relationship and history tasks. In relationship tasks, users need to find and identify relationships between objects, data points, variables, etc. In history tasks, users want to undo or replay previous actions, or return to previous settings or displays. An example of a history function is the "history" tool in many web browsers. Using the history tool, users can see a list of web addresses they have visited in the last several hours, days, or weeks, and return to any previously visited address by clicking the appropriate item in the list.

Examples of visualization tools designed for relationship and history tasks in volume visualization are graph-based [40], spreadsheet-style [23], Design Galleries [33], and parallel coordinates style [57] displays. The graph-based display provides an external representation of the data exploration process (i.e. a complete history), so that users can return to previous images without having to remember which parameter settings (e.g., transfer functions) they used. In addition, the graph shows transfer function relationships between thumbnail views of previously rendered images. The spreadsheet-style interface allows users to explore a range of parameter combinations at the same time and compare the resulting images side-by-side. Similarly, Design Galleries provides a meaningful layout of a wide range of images based on different parameter settings. The parallel coordinates style interface tracks the exploration history, displaying all images in a history bar, and illustrates relationships between images and their parameters via polylines connecting parallel axes (one axis for each visualization parameter).

2D/3D combination displays can provide limited support for relationship and history tasks by displaying multiple images side-by-side. For example, by showing several copies of a single slice, we can display:

- Several types of derived data, such as parametric images (common in functional medical imaging paradigms such as single photon emission computed tomography (SPECT) and positron emission tomography (PET)) or other mathematical functions (e.g. sum, count, average) of the data.
- Various variables for multivariate data (e.g., for medical data, we could draw magnetic resonance imaging (MRI) data for anatomical information and PET data for functional information).
- Several times for time-dependent data.
- Various parameter settings (e.g., colour scales or window and level settings in medical imaging).

Displaying multiple copies of a single 2D view allows users to effectively compare different variables or display settings, and integrate information from the various views. For example, Figure 4.1 illustrates how multiple copies of a 2D view can enhance multivariate data visualization. By using two ExoVis walls plus the 3D overview object, the visualization is able to incorporate three different variables from a fuel cell simulation: temperature, concentration of hydrogen, and concentration of oxygen.

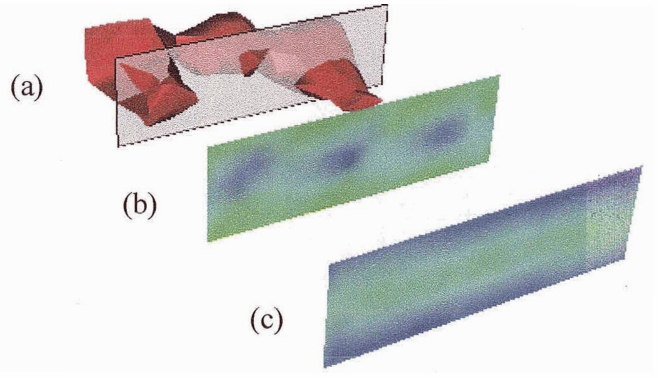


Figure 4.1: Visualization of a multivariate fuel cell data set using ExoVis.
The overview object (a) shows an isosurface of fuel cell temperature. Two copies of a slice show concentrations of hydrogen (b) and oxygen (c). Colour scale shows increasing concentration from green to blue.

Determining how well the fuel cell is functioning may require people to identify areas where hydrogen and oxygen are mixing. By displaying corresponding slices for the two gases side-by-side, this integration task becomes easier than with visualizations that can only display one variable at a time.

Furthermore, if multiple copies of a 2D view are used to show different display settings, history tasks can be simplified. For example, Figure 4.2 illustrates two copies of a slice, each with a different colour scale. Finding good display parameters such as colour scales can be a difficult and frustrating search process, especially if the number of options is large. By creating multiple copies of a 2D view, users can store good display settings in one copy, while simultaneously trying new settings with other copies. This history function can help users avoid losing good settings, and enable them to compare new settings to previous ones.

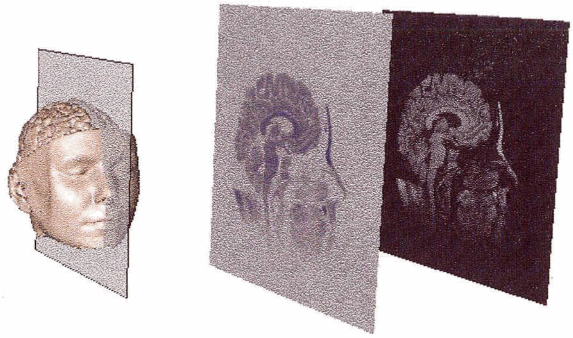


Figure 4.2: Wall copies in ExoVis.
Wall copies can show different rendering styles for the same 2D view.
Here an MRI slice is displayed with two different colour scales.

Creating multiple copies of a 2D view is easy with ExoVis and orientation icons. With an orientation icon, copies are displayed side-by-side in separate windows, and with ExoVis, copies are displayed on a stack of walls, one behind another as in Figures 4.1 and 4.2. By contrast, since more than one slice cannot be displayed in the same place, multiple copies are not possible with the clip/cutting plane approach unless the entire world (i.e., including the 3D view) is re-rendered for each copy.

2 Heuristic Comparison of Techniques

As mentioned in the previous section, each of the 2D/3D display types has advantages and disadvantages. Table 4.1 describes these trade-offs in detail.

Table 4.1: Comparison of In-place Methods, Orientation Icons, and ExoVis

	In-place Methods	*Orientation Icon*	*ExoVis*
Little screen space is required.	✓✓	×	✓
The 3D view is not deformed (cut).	×	✓	✓
Orthogonal 2D slices do not deform (cut) each other.	×	✓	✓

Table 4.1: Comparison of In-place Methods, Orientation Icons, and ExoVis

	In-place Methods	***Orientation Icon***	***ExoVis***
2D views do not occlude each other.	✗ Planes are collocated and may occlude each other.	✓✓ Each view is displayed in a separate space.	✓ Slices can be stacked behind each other.
2D views do not occlude the 3D view.	✗✗ or ✓ Clip planes remove parts of the 3D view, and cutting planes push it aside.	✓ Placeholders can partially occlude the 3D view. ExoVis walls can occlude the 3D view.	✗
Individual 2D or 3D views can be selectively magnified.	✗	✓	✓
It is possible to show several copies of the same 2D view to support relationship and history tasks. E.g., data from several medical imaging modalities (CT, MRI, and US)[a] can be compared (a relationship task) and attention can be easily switched between them (a history task).	✗ Two copies of a plane cannot be shown in the same location, so the 3D view must be re-rendered for each copy.	✓ Since 2D views are shown "out of place", several copies of a single view may be displayed without creating several copies of the 3D view.	✓
2D views are not distorted by being viewed obliquely.	✗	✓	✗
Position and orientation of a 2D view is easy to relate to the 3D model.	✓✓ 2D views are not moved from their original positions.	✗ 2D views are translated and rotated from their original positions.	✓ 2D views are translated but not rotated from their original positions.
When several 2D views are present, it is easy to determine which view corresponds to each placeholder in the 3D overview.	✓✓ Discrimination is trivial since all views are "in place".	✗ Specific cues must be added to make this possible (colour, standard layouts, interactive highlighting, etc.).	✓ Can utilize the same cues as an orientation icon, plus each view is shown in its original orientation.

a. CT = Computed Tomography, MRI = Magnetic Resonance Imaging, and US = Ultrasound.
Scale: ✗✗ ✗ ✓ ✓✓

To summarize, there are several main categories of differences between the 2D/3D combination techniques. We can define evaluation criteria based on these categories:

- **High Integration**: 2D and 3D views should be closely integrated (spatially) to reduce the cognitive overhead required to mentally integrate them.
- **Low Deformation**: 2D and 3D views should deform each other minimally to reduce the cognitive overhead of resolving the deformation.
- **Low Occlusion**: 2D and 3D views should occlude each other minimally.
- **Display Flexibility**: desirable capabilities include the ability to display multiple copies of a 2D view and the ability to selectively magnify views.
- **Minimal Screen Space**: Required screen space for a small set of views should be minimal.
- **Minimal Screen Space Growth**: Required screen space should grow minimally when extra views are added.
- **Minimal Oblique Viewing**: display techniques should allow users to observe 2D views non-obliquely.

A summary evaluation of clip/cutting planes, orientation icons, and ExoVis using these criteria is given in Table 4.2.

Table 4.2: Summary Comparison of 2D/3D Combination Methods[a]

	In Place Methods	*Orientation Icon*	*ExoVis*
High Integration	✓✓	×	✓
Low Deformation	×	✓✓	✓✓
Low Occlusion	×	✓✓	✓
Display Flexibility	×	✓✓	✓✓
Minimal Screen Space	✓✓	×	✓
Minimal Screen Space Growth	×	✓	✓✓
Minimal Oblique Viewing	×	✓✓	×

a. Legend: ✓✓ (strongly satisfies criterion), ✓ (moderately satisfies criterion), × (weakly satisfies criterion or does not satisfy criterion).

As a final note, hybrids of the three basic approaches are possible. For example, a 3D view could be displayed in one window as an “orientation icon”, and several orthogonal slices could be displayed together “in place” in a second window (without any 3D object). In this case, the 2D views are “in place” with respect to each other but “out of place” with respect to the 3D view. Advantages and disadvantages of such hybrid techniques can be inferred from tables 4.1 and 4.2.

Chapter 5: Task by Display Type Analysis

As discussed in Chapter 2, 2D and 3D views are useful for different tasks. Therefore, we would expect that the usefulness of 2D/3D combination displays will also vary with the task to be performed. In addition, different tasks will benefit from different types of 2D/3D combinations. This chapter develops a theory that predicts which types of tasks may benefit from a combination of 2D and 3D views, and which type of combination will be most beneficial. Some predictions made by this theory are tested through user studies in the following chapters.

This chapter is organized as follows. It begins by identifying common tasks involving visualizations. The tasks are general rather than domain specific so that the theory and its predictions will be valuable to a wide variety of domains. For this reason, visualization subtasks are considered, rather than complicated higher-level tasks. After identifying the subtasks, each one is analyzed in detail, including:

- Examples from several application domains,
- Advantages and disadvantages of 2D and 3D views,
- Author's predictions about when 2D/3D combination displays would be useful, and
- Author's predictions about which 2D/3D combination displays would be most valuable.

1 Visualization Subtasks

To define a set of domain-independent visualization subtasks, visualization tasks common to many disciplines were identified and classified into a small number of domain-independent categories. Three substantially different domains that make use of both 3D and 2D visualization techniques were considered: medical imaging, computer aided design (CAD), and geographic information systems (GIS). These domains were chosen because they have substantially different data, users, and goals. Thus, tasks common to two or three of these domains should be common in many other application domains as well; this makes them good candidates for a generalized study.

Books were examined in each area (see [12], [15], [19], [30], and [36]) to generate a list of visualization subtasks performed in each discipline. Subtasks were then organized to identify a minimal set of domain independent task categories. The resulting set of categories were:

- **Search and Filter**: search for a target object, location, feature, or pattern. This may involve visual search and /or filtering to show only those items that match designated criteria.
- **Information Look-Up**: query for specific information (exact values).
- **Navigate**: plan and control the position, orientation, and course of a camera or manipulable object.
- **History:** return to previous views or states. Typically related to navigation, filtering, or construction.
- **Relate**: identify relationships between objects, data sets, and/or events (e.g., comparisons, connections, relative locations, or trends).
- **Construct**: Create data through modeling or annotation.
- **Measure**: estimate or calculate numerical values (e.g., distance or area).
- **Group/Classify**: mentally or physically organize objects into meaningful categories.
- **Mental Registration and Integration**: make connections between different views of a data set when several views are used to perform a task.

The categorization given above is not the only one possible, and represents only a small part of the visualization process. Springmeyer *et al.* conducted an empirical study of people doing data analysis in several disciplines, and developed the task characterization given in Figure 5.1 [50]. This categorization provides a higher-level view of data analysis tasks than the categories above. Springmeyer *et al.* organize data analysis into two major categories: "....exploring the data to extract information or confirm results (Investigation), and assimilating the resulting knowledge (Integration of Insight)" [50, p. 238]. A further breakdown of these categories yields "interacting with representations" (how people use representations of data), "applying math" (deriving mathematical values), "maneuvering" (organizing data, choosing tools and representations, and setting up representations), and "expressing ideas" (recording and describing observations, ideas, and insight) [50].

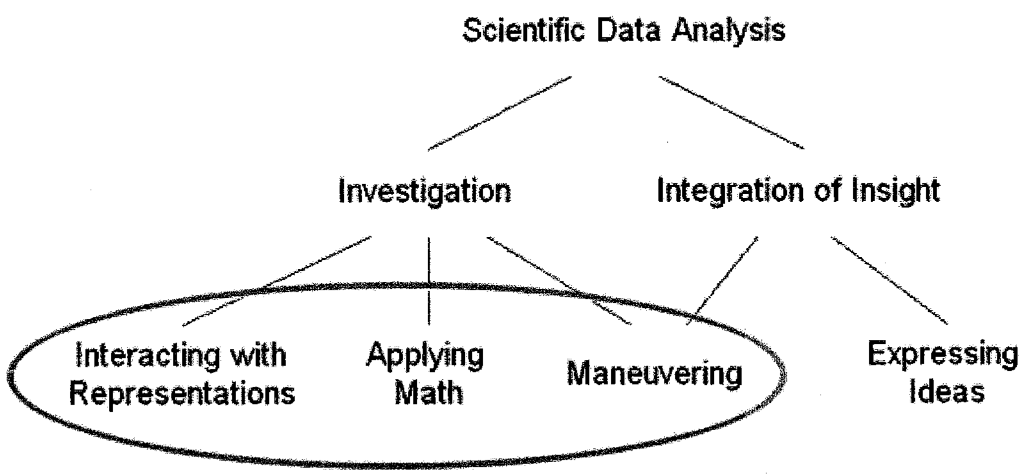


Figure 5.1: Characterization of the scientific data analysis process[1].
Blue ellipse indicates where my task categories belong in this scheme.

Because the thesis focuses on how *visualization characteristics* affect task performance, the task classification used in the thesis contains only those tasks involving data representations. This categorization fits into the larger scheme under "investigation", specifically "interacting with representations". It also has some relationship to "applying math" and "maneuvering", but only when those operations involve visual representations.

1. Based on [50], Figure 2 (Categories of process elements) on p. 238.

See the blue ellipse in Figure 5.1. A more specific illustration of the relationships between task categories used in this thesis and those from Springmeyer *et al.* is given in Table 5.1, along with an earlier classification system by Wehrend [67]. Categories used in this thesis are similar to the subcategories under "interacting with representations", with the addition of a few other tasks relating to representations.

Table 5.1: Comparison of visualization subtask classifications

Tory (2004)	Springmeyer (1992)	Wehrend (1990)
Search and Filter	*Examine* (Interacting with representations) and *data culling* (Maneuvering)	*Identify, locate*
Information Look-Up	*Query* (Interacting with representations)	--
Navigate	*Orient* (Interacting with representations) and *navigate* (Maneuvering)	--
History	--	--
Determine Relationships	*Compare* (Interacting with representations)	*Distinguish, compare, relations, associate, correlate, rank, distribution*
Construct	*Generate* (Interacting with representations), *derive new conditions* (Applying math)	--
Measure	*Calculate* (Applying Math)	--
Group/Classify	*Classify* (Interacting with representations)	*Categorize, cluster*
Mental Registration and Integration	--	--
--	*Manage data* (Maneuvering)	--
--	*Generate statistics* (Applying math)	--

Table 5.1: Comparison of visualization subtask classifications

Tory (2004)	Springmeyer (1992)	Wehrend (1990)
--	*Record* and *describe* (Express ideas)	--

Although the thesis could have used Springmeyer's categories directly, a new classification system was created for a number of reasons:

- The new classification system avoids the complexity of being hierarchical. Since the thesis only deals with the subset of visualization tasks that involve representations, this keeps the classification simple.
- In Springmeyer's classification, "applying math" and "maneuvering" are separate categories from "interacting with representations". However, some math and maneuvering tasks involve representations.
- Some tasks in Springmeyer's classification system were not adequately represented. For example, determining relationships includes more than simply making comparisons. Other types of relationships could be relative locations of objects, trends over time, or connections between objects. Similarly, measurement can include estimation in addition to computer-based calculation.

2 Task by Display Type Analysis

In this section, the visualization subtask categories are described in more detail, with examples from each of the three disciplines studied. Specific predictions are then made regarding when 2D, 3D, and combined 2D/3D views would be most appropriate for each category.

2.1 Search and Filter

Searching involves looking for a target object, location, feature, or pattern. This process may involve visual search and /or filtering to hide or show items that match criteria of interest to the user. Examples of search and filter tasks are given below:

MEDICAL IMAGING

- Search for a structure (liver, kidney, etc.) or anomaly (tumour, lesion, etc.)
- In functional imaging, search for activity patterns on parametric images or search for groups of pixels with similar activity trends.
- In slice viewers, changing which slices are visible.
- Changing visibility of parts (e.g., by moving a clip plane, adding/removing segmented structures from view, or setting isovalues or transfer functions).

CAD

- Search for a particular object or location in a model.
- Changing visibility of parts (e.g., by setting clipping plane positions, adding/ removing layers, or switching between wireframe and surface views).

GIS

- Search for objects, areas, or volumes with specific features (e.g., homes with a certain number of children or ore deposits with quality ratings greater than a threshold).
- Route planning - search for the quickest, cheapest, or safest route from A to B.
- Controlling what data items are displayed (e.g., by query or by adding/ removing layers).
- Changing visibility of spatial areas (e.g., by setting clipping plane positions).

Table 5.2: 2D and 3D Views in Search and Filter Tasks

Benefits of 2D views	Benefits of 3D views
Target will not be occluded in all 2D views.	3D views provide a good overview of an entire 3D space, so there is no need to scroll through a large number of views (e.g., slices).
Visual search is good at identifying 2D patterns.	Targets with complex 3D shapes may be easier to identify with a 3D view.

Combinations of 2D and 3D views may be useful when:

- The target has a complex 3D shape and other objects in the scene obscure the target in many 3D views.

- The number of 2D slices is very large. In this case, the 3D view may function as an overview to identify objects that may be the target, and then 2D views can be used to confirm this conjecture.
- The general vicinity of the target is known. Here a 3D overview can be used to get close to the target and the 2D views can be used for a refined search.

In addition, filtering sometimes requires navigation (e.g., a user may adjust a clip plane for the purpose of filtering out items in front of it, but the act of moving the clip plane involves navigation). Hence 2D/3D combinations may be useful when navigation is required to perform a search and filter task and the navigation part of the task can benefit from both 2D and 3D views. (See section 2.3 for more details on navigation.)

Which type of 2D/3D combination view is best for search tasks?

Search tasks probably require a minimal number of views (e.g., one 3D view and 1-2 2D views), so problems with screen space, display flexibility, occlusion, and deformation are not likely.

- If both the 2D and 3D views are directly involved in the search task, it may be beneficial to have the views closely integrated. Thus, an "in place" approach (such as clip or cutting planes) may be best.
- However, if the target has similar shapes to other objects in the scene, it may be difficult to identify the target at oblique angles, so an orientation icon display may be best.

2.2 Information Look-up

Information look-up involves querying the system for exact values. Examples of information look-up tasks are:

MEDICAL IMAGING

- Determining disease state of a particular organ.
- Finding the time-activity curve at a certain pixel.

CAD

- Looking up material properties of an object.

- Determining exact coordinates of an object.

GIS

- Finding what exists at a specific geographic location.
- Looking up the name of a street.

Table 5.3: 2D and 3D Views in Lookup Tasks

Benefits of 2D views	Benefits of 3D views
Easy to identify target location by pointing.	Some properties of 3D objects may be represented by their colour, texture, etc. This allows us to look up the properties by simply viewing a 3D representation.
Easy to read text at target location.	

Although it is possible that combinations of 2D and 3D views could be useful for lookup tasks, an example scenario where this would be expected could not be identified.

2.3 Navigate

Navigation involves traversing an interface, virtual world, or data set. It consists of two components: a cognitive activity called wayfinding (e.g., Where am I? Where do I want to go?) and the actual movement, called travel. Examples of navigation include:

MEDICAL IMAGING

- In slice viewers, changing which slices are visible and manipulating the hanging protocol (how the viewing space is organized).
- Moving the viewpoint in 3D (e.g., along a path through the colon in virtual colonoscopy).
- Orienting or translating a slice/clip plane.
- Positioning a cursor (in 2D or 3D) to prepare for other tasks (such as picking a point, sculpting, or drawing a region of interest).

CAD

- Changing the viewpoint in 3D or zoom and pan in 2D.
- Orienting and positioning a view plane or clip plane.

- Positioning a cursor (in 2D or 3D) to prepare for drawing.

GIS

- Changing the viewpoint in 3D or zoom and pan in 2D.
- Adjusting the type of display (e.g., map, graph, list).
- Orienting or translating a slice/clip plane in a volume data set (e.g., as in stratigraphy), or setting up multiple cross-sections to form a "fence diagram".

Table 5.4: 2D and 3D Views in Navigation Tasks

Benefits of 2D views	Benefits of 3D views
Exact positioning is easy.	May provide more natural and more immediate feedback for positioning viewpoint, cursor, or objects in 3D.
Useful for tasks that do not involve 3 spatial dimensions simultaneously.	

Combinations of 2D and 3D views may be useful when 3D knowledge is important for performing the task, but exact positioning is required. Examples may include:

- Orienting a 2D plane (clip plane, slice plane, or view orientation) within a 3D space.
- Placing the cursor at an exact position in 3D space.

Combinations of 2D and 3D views may also be beneficial when a higher level task requires the user to frequently switch back and forth between 2D and 3D views, even if no single part of the task requires both types of views at once. For example, a medical imaging task might be to find Multiple Sclerosis lesions in the brain and then estimate their volume. Searching for the lesions may be easier with 2D slice views since there is a lot of occlusion in medical imaging data sets. It may also be easier identify a lesion via pointing with a 2D view (because there is no ambiguity). However, it may be easier to estimate volume with a 3D model of the identified lesion. Continually switching back and forth between the 2D and 3D views may take time and effort for the viewer to understand their relationships to one another. By contrast, if both views are visible simultaneously, this switching may be avoided or made easier, increasing task performance.

Which type of 2D/3D combination view is best for navigation tasks?

3D navigation tasks such as positioning a cursor or setting a view plane orientation will likely involve one 3D view and several 2D views from different angles (most likely 3 orthogonal 2D views). Screen space and display flexibility are therefore not too important, but occlusion, deformation, ease of integration, and oblique viewing could have effects. Because such tasks require significant integration between views, ease of integration is probably the most important factor. However, with several 2D views, occlusion and deformation could become problematic for "in place" techniques, suggesting that an "out of place" method is more appropriate. Although oblique viewing could also have some negative effects, these are likely less problematic to users than difficulty integrating the various views; therefore, ExoVis is predicted to be the best method.

For higher level tasks that require frequent switching between 2D and 3D views, high integration between 2D and 3D views is less likely to be important, and may even be undesirable if the subtasks are better performed on individual views (especially if integrating the views causes occlusion or deformation). In this case, any "out of place" technique (e.g., orientation icon or ExoVis) is probably most appropriate. Which of these "out of place" techniques is best will depend on how much integration among 2D views is required by the subtasks.

2.4 History

A history task is a specific type of navigation or filtering task, in which the goal is to return to a previous view (e.g., to see a previous data set, representation, and/or display setting). It may also be a specific type of construction task, in which the goal is to undo previous editing. Examples of history tasks are:

MEDICAL IMAGING

- Returning to a previous image or group of images for a follow-up study.
- Returning to a previous transfer function (3D), camera angle (3D), window and level (2D), or other display setting.

CAD

- Returning to a previous camera angle.

- Undoing changes to the model being edited.

GIS

- Returning to a previous camera angle.
- Returning to previous filter or display settings.

It can be difficult for users to remember all the changes they have made, so reversing these changes later on may not be possible. Thus, history tasks are probably best supported by tracking and displaying changes users have made (e.g., navigation, filtering, and construction changes) and allowing users to go back to any previous state by moving through the history representation. Although it may be possible to represent the history using a 3D visualization, it is probably easier to represent it using a simple undo button and/or a 2D list, chart, or graph (e.g., like the history list in a web browser). As such, combinations of 2D and 3D views may not be useful for history tasks.

If a dedicated history function is not available, then users perform history tasks by reversing previous navigation, filtering, or construction tasks. In this case, 2D and 3D views will be valuable if they are useful for the specific navigation, filtering, or construction task being performed. (See sections 2.1, 2.3, and 2.6 for a description of when 2D and 3D views can be useful for filtering, navigation, and construction.)

2.5 Relate

Many tasks require users to determine relationships between different data points. Several examples are:

MEDICAL IMAGING

- Identifying physical or functional relationships between structures, including containment and connectedness relationships.
- Identifying trends or changes over time.
- Comparing data sets to determine differences (one patient at two times, two patients, or two parts of one patient, such as right and left knees). For example, the right knee may be considered "normal" so that anomalies in the left can be identified by comparison.

- Integrating information across imaging modalities.

CAD

- Determining whether two objects are connected or interfere.
- Determining relative positions, orientations, or sizes of objects.
- Determining whether one object is contained within another.

GIS

- Proximity analysis - determining where an object or set of objects exists relative to another. This may be done by comparing two types of objects on one map or by comparing two separate maps of the same area.
- Determining if two objects are connected (e.g., by a road).
- Line-of-sight mapping for landscape analysis - can a target be seen from a viewpoint?
- Comparison of some variable at two locations (e.g., population or amount of greenspace).
- Determining the relationship between object shape and a functional occurrence (e.g., 3D topography of a clay layer can affect underground water dynamics).

Table 5.5: 2D and 3D Views in Relationship Tasks

Benefits of 2D views	Benefits of 3D views
Overlapping slices for comparison may be easier than overlapping 3D views since occlusion is reduced.	3D physical shapes and relationships (e.g., connections) may be easier to see in 3D.
Objects are less likely to be occluded than in 3D (e.g., it may be easier to see containment relationships with slices).	
Positional relationships may be easier to determine because depth is not ambiguous.	

Combinations of 2D and 3D views may be useful when:

- Precise positional relationships (e.g., relative position or distance apart) must be determined but the relationship is 3D in nature.

- 3D relationships (e.g., physical connections or relationships involving 3D shape) must be determined but the target objects are occluded in 3D.
- Multiple relationships must be identified (e.g., 3D connectivity as well as containment).

Which type of 2D/3D combination view is best for relationship tasks?

For 3D positional relationships or connections, close integration of 2D and 3D views may be quite important. If several 2D views are involved, however, occlusion and deformation could be a problem for "in place" methods. In addition, display flexibility is likely to be useful (e.g., we may want to display several slices from the same orientation to see if a structure intersects all of them). These trade-offs imply that ExoVis may be the best type of 2D/3D combination view for many relationship tasks.

2.6 Construct (Annotation and Modeling)

Examples of construction tasks are:

MEDICAL IMAGING

- Picking or outlining structures (e.g., for segmentation). This may be 2D (regions of interest) or 3D (volumes of interest), and may be done by picking points, placing primitive shapes, or manual drawing.
- Drawing lines (e.g., for distance measurements).
- Tagging images for future reference.
- Adding and removing structure by either sculpting or placing primitive shapes (e.g., for surgery planning).

CAD

- Modeling by drawing lines and primitives. This may be either 2D or 3D, and may involve operations on basic primitives (subtract, union, intersect, etc.).
- Picking points or objects.
- Aligning, rotating, and scaling objects or lines.
- Annotations - dimensions, part numbers, etc.

GIS

- Modeling a process over time to predict the effect of some variable on another.
- Constructing a digital map from other digital maps or non-digital information.
- Generating 3D models from a limited number of sample points. This may involve both automated modelling and manual editing of the model.

Table 5.6: 2D and 3D Views in Construction Tasks

Benefits of 2D views	Benefits of 3D views
Drawing or picking points on a 2D plane is easy.	Shape of 3D model may be easier to understand
Positions are not ambiguous. Objects can be easily placed and aligned.	3D information may be valuable for positioning the cursor or objects relative to other objects in a 3D space.
Target position or object will not be occluded in all 2D views.	

Combinations of 2D and 3D views may be useful for:

- Positioning a cursor in 3D space
- Drawing and positioning 3D objects

Which type of 2D/3D combination view is best for construction tasks?

- For drawing arbitrary shapes, non-oblique viewing is likely very important and the orientation icon (or some version of another technique where a 2D view can be selected and viewed straight-on) is probably best.
- For positioning a cursor or primitive shape, integration of 2D and 3D views is probably very important. With a small number of views, "in place" techniques are probably best since they provide the best integration. However, with more views, occlusion and deformation could cause problems, so ExoVis may be more appropriate.

2.7 Measure

Measurements may involve either *visual estimation* or computer-based *calculation.* Examples include:

MEDICAL IMAGING

- Measuring distance between two structures.
- Determining area or volume of physical structures or, in functional imaging, activated areas.
- In functional imaging, determining uptake/washout rates, activity counts, or time/concentration curves for a region or volume of interest.

CAD

- Measuring distance or angle between two objects.
- Determining area or volume of an object.
- Calculating cost of materials for a construction plan.

GIS

- Measuring distances, thicknesses, areas, and volumes.
- Determining the proportion of certain objects within an area or volume.
- Calculating summary information (e.g., average population in a province).
- For landscape analysis, determining slope, aspect, convexity, concavity, etc.

Table 5.7: 2D and 3D Views in Measurement Tasks

Benefits of 2D views	Benefits of 3D views
Distances and angles are not distorted. Easier to estimate distance, angles, and area.	Easier to estimate volume since integration between multiple 2D views is unnecessary.
Input and output of exact calculations may be easier to specify and read.	Easier to estimate 3D shape.

Although it is possible that combinations of 2D and 3D views could be useful for measurement tasks, an example scenario where this would be expected could not be identified.

2.8 Group/Classify

Classification is a mental or physical activity of organizing objects into meaningful categories. Examples include:

MEDICAL IMAGING

- Grouping pixels or objects into organs and higher level structures - either mentally or through modeling or segmentation.
- Organizing medical images into groups to facilitate comparison.

CAD

- Grouping primitives into higher-level objects.
- Layering.

GIS

- Layering.
- Organizing data into categories, or re-organizing existing categories (e.g., reclassifying points with language data into English-speaking vs. non-English speaking).
- Aggregating data into higher level groups (e.g., displaying population by province or electoral district).

Classification is usually a higher-level task involving several subtasks and possibly some user interface operations. For example, a physical grouping operation in CAD may involve drawing several primitives and selecting them (construction tasks) and then specifying that they belong together (through some interface widget). Similarly, mental classification in medical imaging may involve locating certain structures (a search task) and determining how they are related (a relationship task). As such, the usefulness of 2D and 3D views for a grouping/classification task are best determined by the usefulness of each type of view for the specific subtasks involved.

2.9 Mental Registration and Integration

Any task involving multiple views requires users to mentally integrate information across those views, or at least to understand the relationship between the views (registration). Several examples are given below:

MEDICAL IMAGING

- Rapidly animating a set of 2D slices to build a mental model of 3D structure (cine mode).
- Integrating across several imaging modalities (e.g., functional and anatomical images).
- Localizing a structure relative to an atlas or other reference image.
- Viewing coronal, saggital, and axial 2D views of the body.

CAD

- Using overview and detail type displays.
- Using multiple views (typically some combination of orthogonal 2D views and 3D views) to study or construct objects.

GIS

- Registering multiple views of the same area (typically some combination of cutting planes from various orientations and several different 3D views).

Mental registration is a subtask of any task that requires users to make use of several physically or temporally separated views of one area. Different ways of combining 2D and 3D views can be expected to affect the ease of the mental registration subtask. Specifically, higher physical integration between the views should make mental registration easier. Thus, mental registration should be easiest with "in place" methods, moderately difficult with ExoVis, and most difficult with completely separated views such as the orientation icon.

3 Summary: List of Potential Tasks

The goal of this chapter was to obtain a list of tasks that may benefit from having combinations of 2D and 3D views. These tasks should be generic (i.e. not specific to a particular application domain) and should be commonly performed in the course of real work. The resulting list is as follows:

1. Visual search for a target with a complex 3D shape, where other objects in the scene obscure the target in many 3D views.
2. Visual search for a target in a dense space, when the number of 2D slices is very large and/or the general vicinity of the target in 3D is known.
3. Orienting a 2D plane (clip plane, slice plane, or view orientation) within a 3D space. [This task was involved in the experimental study in Chapter 8.]
4. Placing the cursor at an exact position in 3D space.
5. Drawing and positioning 3D objects in 3D space. [This task was involved in the experimental study in Chapter 9.]
6. Identifying precise positional relationships that are 3D in nature (e.g., relative positions of objects or their distance apart). [This task was involved in the experimental studies in Chapters 8 and 9.]
7. Identifying 3D relationships (e.g., physical connections or relationships involving 3D shape) when the target objects are occluded in 3D views.
8. Identifying multiple relationships, where some are easiest to identify with 2D views and others with 3D views (e.g., 3D connectivity and containment).
9. Any scenario that requires users to frequently switch back and forth between 2D and 3D views.

Chapter 6: Overview of Experiments

1 Summary Figure

Figure 6.1 provides an overview of the experiments performed in this thesis and the chapters where each experiment may be found.

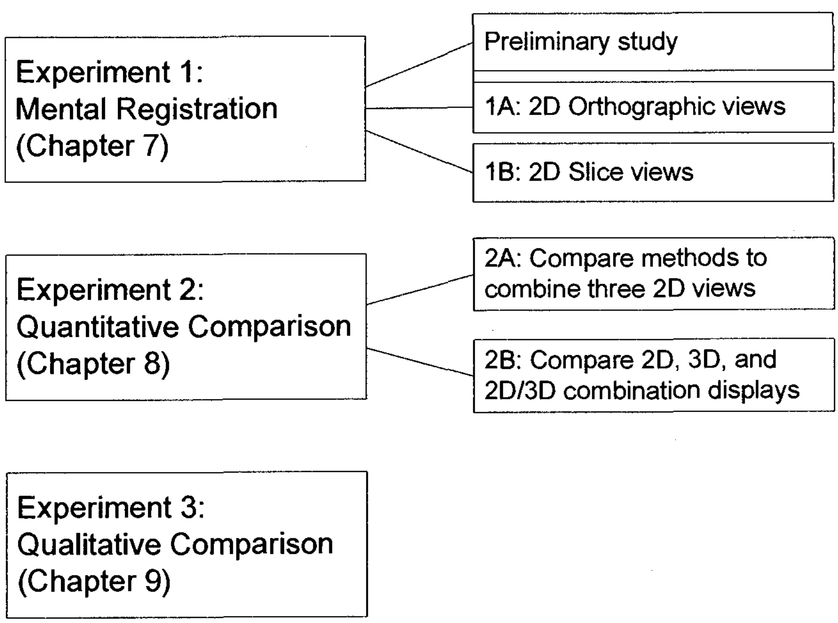


Figure 6.1: Brief description of each experiment.

2 Experiment 1: Refining the Theory

Chapters 4 and 5 developed a theory about when both 2D and 3D displays are useful for visualization tasks, and how to combine 2D and 3D views most effectively. This theory depended on an important assumption that was not supported (or contradicted) by existing empirical evidence. Specifically:

> When various 2D and 3D views are combined, there is a substantial mental registration cost if the views are not spatially integrated. This cost is greater when 2D views are both translated and rotated from their original positions (e.g., with the orientation icon) than when they are translated but not rotated (e.g., with ExoVis).

Experiment 1 tested this mental registration assumption and determined the relative difficulty of mental registration for each 2D/3D combination method. First, a preliminary study was performed to determine whether view orientation was important and to establish criteria for creating experimental stimuli. Then, two main studies were conducted: experiment 1A considered 2D orthographic projections and experiment 1B considered 2D slices. Results supported the hypothesis above. Details may be found in Chapter 7.

3 Experiments 2 and 3: Testing the Theory

Chapter 5 identified several visualization subtasks that were predicted to benefit from a combination of 2D and 3D views. Chapter 5 also predicted which type of 2D/3D combination would be best for each of these subtasks. Chapters 8 and 9 describe two experiments that test which display types are best for a few visualization subtasks.

Experiment 2 (see Chapter 8) compared 2D, 3D, and 2D/3D combination displays for two visualization subtasks:

- *Relative positioning:* Determine the relative position of two objects.
  (A relationship task.)

- *Orientation:* Orient a plane in 3D space (e.g., for 3D modelling or to orient a clip or view plane). (A navigation and construction task.)

These tasks were chosen because they are well defined, cover more than one task type, and are common in many application domains. Other tasks identified in Chapter 5 do not satisfy these criteria. For example, search tasks were predicted to benefit from combination 2D/3D displays when the target had a complex 3D shape and the search space was large and dense. This task is not well defined because "complex 3D shape" and "dense space" are vague concepts.

Because there were many different displays under consideration, experiment 2 was split into two sub-studies to simplify the experimental design:

- Experiment 2A compared three methods for combining three orthogonal 2D views in an orientation icon display. The best of these three methods was then subjected to further testing in experiment 2B.
- Experiment 2B compared 2D views alone, 3D views alone, orientation icon displays, ExoVis displays, and in-place displays.

Experiment 2 relied primarily on quantitative measures such as timing and errors, with limited qualitative analysis. Strict controls were put in place to enable meaningful quantitative comparisons of the displays. Interactivity was particularly limited; for example, participants could not rotate 3D views or change 2D slice positions. In addition, experiment 2 used abstract data sets (block shapes, spheres, tori, etc.) so the results could be applicable to many domains. It is not certain that results based on these data sets and tasks would be identical for real world situations. Experiment 3 (see Chapter 9) was a qualitative exploration that addressed these issues.

Chapter 7: Experiment 1 - Mental Registration

1 Overview and Objectives

One important difference between 2D/3D display techniques is how easily users can relate and integrate information from different views. Users must understand relationships between views to make sense of the data. Mental registration can be defined as a mental transformation in which two or more views of the same data are aligned spatially. For example, an x-y slice of a volume can be mentally registered with a y-z slice by mentally rotating 90° around the y-axis. Mental registration can be challenging and requires cognitive resources [38][42]. Since mental registration is performed very often in multi-view systems, displays should be designed to make it easy. One factor affecting the difficulty is the method of combining 2D and 3D views. The study in this chapter investigates mental registration difficulty for different 2D/3D combination displays and proposes reasons for the differences. The displays are considered generically so that the results are applicable to many visualization domains.

Specific objectives of this mental registration study are to:

- Determine the relative cost (in time and difficulty) of mentally registering one 2D and one 3D view when
  - They are spatially separated from one another (as with both ExoVis and orientation icons), and

    - The placeholder and 2D view have different orientations (as with orientation icons).
- Determine how this cost varies with orientation of the 2D view (top, right, or front aligned 2D views).
- Determine whether this cost is different for 2D orthographic projections as compared with 2D slices.

Although the eventual goal is to study complex situations (e.g., many different 2D views, data sets, etc.), the current study is limited to static displays of block shapes, with one 2D and one 3D view and only top, front, and right 2D view orientations. This allows us to isolate the factor of interest (mental registration) and avoids complicating the analysis with a large number of variables. Also, axis-aligned 2D views are very common in many applications. More complicated displays are considered in chapters 8 and 9.

2 Preliminary Study

A preliminary study was run in preparation for experiment 1. This preliminary study had several objectives:

- Determine what made the stimuli (block objects) simple or complex, and how shape complexity affected mental registration. These results allowed me to develop a good set of shapes for the main experiment.
- Determine if there was a measurable difference between top, front, and right 2D view orientations.
- Verify that the experimental procedures and software were appropriate.

2.1 Design

The preliminary study investigated the effect of shape complexity and view orientation on a 2D/3D mental registration task. Independent variables were shape and 2D view orientation, and dependent variables were time, accuracy, and ratings of difficulty. A 10 x 3 within-subjects design was used, with one trial of each condition. Order of the conditions was pseudorandom. Figure 7.1 illustrates the experimental conditions.

	2D view orientation		
	Top	Right	Front
Shape 1			
Shape 2			
...			
Shape 10			

Figure 7.1: Experimental conditions for the preliminary study.

2.2 Method

2.2.1 Task

Participants mentally registered 2D and 3D views of a block shape to identify a corresponding part. Specifically, participants were shown one 3D view and one 2D orthographic view of a block shape, placed side-by-side (an orientation icon display). Block shapes consisted of small cubes "glued together" to form a larger structure. In the 3D view, one cube was red and all others were grey. In the 2D view, all cubes were grey, and five of the cubes contained a unique uppercase letter (from A to E). Participants identified the letter that corresponded to the red cube. The number of possible answers was limited to five to ensure all trials had the same number of possible answers. Three sample trials are shown in Figure 7.2.

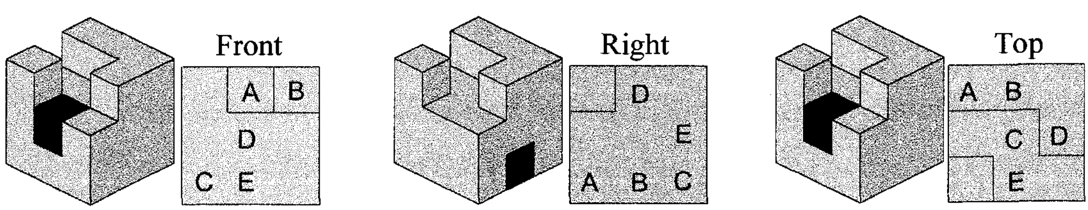


Figure 7.2: Sample tasks from the preliminary study.
Participants mentally register the 2D and 3D views to identify the letter corresponding to the red block. Each trial showed a front, right, or top 2D orthographic projection of the block shape. Correct answers are D (Front), B (Right), and E (Top).

2.2.2 Stimuli

Block shapes were modelled in Trispectives Technical version 2.0. Following Shyi and Huang [48], the blocks were generated by removing 2, 5, or 8 cubes (size 1 x 1 x 1) from a base shape containing 27 cubes (3 x 3 x 3). Example block shapes are shown in Figures 7.2 and 7.4. Removal of cubes was constrained such that:

- The resulting object remained as a single connected component and was not allowed to lose its 3 x 3 x 3 structure (i.e., no 3 x 3 slab was completely removed).
- Cubes were removed contiguously from either one or two locations, but not from more than two locations.

All 3D views were rendered with isometric projection to make the figures appear as small objects (e.g., toys) viewed up close. 2D views were rendered from the top, right, and front faces of the object, following the ANSI standard (third-angle projection).

Cube-based stimuli were chosen so the identification task could not be done without mentally registering the 2D and 3D views. Specifically, the target could not be identified by simply looking for a particular shape among other shapes. The Shyi and Huang [48] shapes were selected for the following reasons:

- The shapes have interesting contours in 2D orthographic views and slice views. Block figures such as those used by Shepard and Metzler [47] do not have interesting contours on all 2D slices. This was not important for the preliminary study but was necessary for the main experiment, which considered both 2D slice views and 2D orthographic views.
- The number of squares on the 2D views does not vary greatly. This equalizes the number of possible answers for each trial. This possible confounding factor was also reduced by having exactly five possible answers. For views with more than five cubes, some of the cubes did not contain a letter and could not be the correct answer (e.g., see the spaces without letters in Figure 7.2).

A total of 13 block shapes were created. 10 were used in the experimental trials and 3 were used for practice trials and documentation. In the experimental trials, participants saw each block shape 3 times, once with each 2D view orientation (front, right, or top). Stimuli were presented as static images. A text label centred above the display indicated the current view orientation, as shown in Figure 7.2.

2.2.3 Participants

Five computer science graduate students and one computer science faculty member were recruited from Simon Fraser University. One participant was female and the others were male. Most participants had some familiarity with 3D computer graphics.

2.2.4 Experimental Set-Up

Custom experimental software was written in Java and run on a Pentium laptop computer with 160 MB of memory and 800 x 600 display resolution. No other processes were run on the computer during the experimental sessions. Participants interacted with the computer using an external mouse. The keyboard was not used.

2.2.5 Procedure

Participants completed 6 practice trials followed by 30 experimental trials (10 with each view orientation x 3 with each shape). Shapes and view orientations were in pseudo-random order. All participants completed the same trials. The experimental procedure was as follows:

1. Review instructional materials that explain the 2D and 3D views and give example trials with correct answers. Resolve any confusion about the task by asking the experimenter for help.
2. Complete 6 practice trials, asking the experimenter for help if necessary.
3. Complete 30 experimental trials.

The experimenter observed participants during the experimental trials but did not interact with them.

Participants were instructed to be as accurate as possible, but were asked not to take a break during the middle of a trial since they were being timed. Taking a break between trials was permitted. Each trial began when the participant pressed a "Ready" button and ended when they clicked one of five buttons at the bottom of the screen (labelled

"A", "B", "C", "D", or "E") to select their answer. No time limit was imposed. Answers could not be changed.

Participants filled out a background questionnaire (see Appendix 2) prior to the experimental trials. In a post-trial questionnaire (see Appendix 2), they rated the difficulty of performing the study task with each view orientation (top, right, and front) and rated the complexity of each block shape. Participants were then invited to ask any questions or share any comments with the experimenter.

2.2.6 Measures

For each trial, the computer recorded the participant's response and start and end times. Total time and accuracy were computed after the experiment was completed. Participants recorded self-reports of difficulty (on a 7-point rating scale) and shape complexity (on 10-point rating scales) in the post-trial questionnaire (see Appendix 2). Participants' comments were recorded by the experimenter.

2.3 Hypotheses

H7.1. Shapes rated as more complex would require more time, but errors would not be affected.

H7.2. View orientation would not affect task time or errors.

2.4 Results

2.4.1 Ratings of Shape Complexity

Shape complexity fell into approximately 3-4 categories, as shown in Figure 7.3.

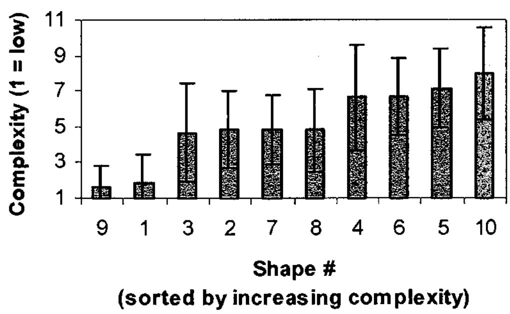


Figure 7.3: Average shape complexity ratings

An analysis of the shapes themselves indicated that:

- **Very simple shapes** (shapes 1 and 9) could be created by adding or subtracting two block-shaped primitives of arbitrary size. In other words, the shapes contained only one "hole" in or "addition" to a size *l* x *n* x *m* base shape.
- **Moderately complex shapes** (shapes 2, 3, 7, and 8) could be created by adding or subtracting three block-shaped primitives of arbitrary size (the shapes contained two "holes" in or "additions" to a size *l* x *n* x *m* base shape).
- **Complex & Very complex shapes** (shapes 4, 5, 6, and 10):
    - Required at least three block-shaped primitives (of arbitrary size) to create the shape, and usually more than three.
    - Had a more complex "hole".
- **Very complex shapes** (shape 10) had some complicated contours that were partially hidden around the back or bottom of the object.

Examples of shapes with different complexities are given in Figure 4.

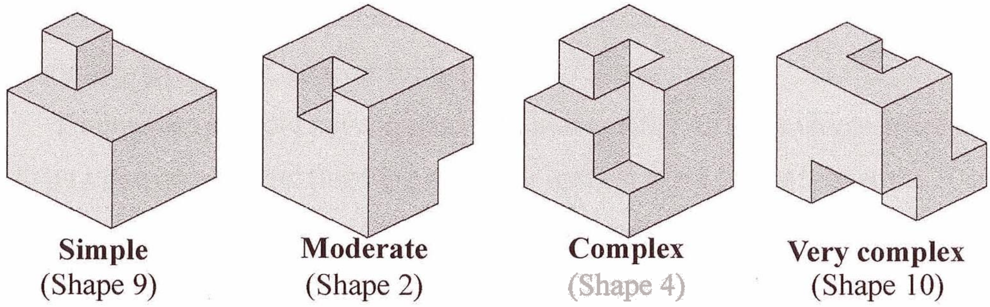
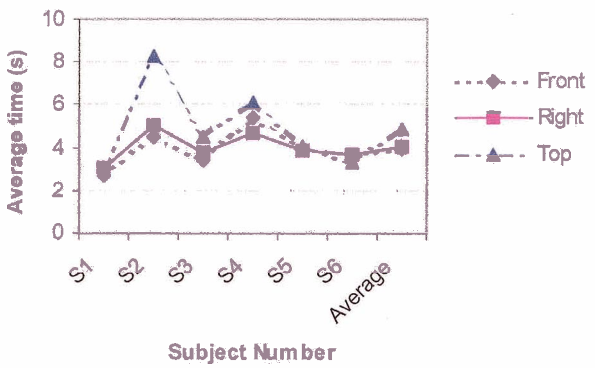


Figure 7.4: Example shapes with varying complexity ratings

In summary, the best predictors of shape complexity seem to be (1) minimum number of *l* x *n* x *m* primitives required to make the shape, (2) complexity of "holes" and (3) hidden contours.

2.4.2 Timing Results

Overall, several participants (particularly S2) required the most time for top views, as shown in Figure 7.5. This contradicts hypothesis 7.1. A likely explanation is that a larger mental rotation [47] is required to align top views with a 3D view as compared with front and right views.



Standard Deviations

	Front	*Right*	*Top*
S1	0.4	0.8	0.7
S2	1.7	3.2	5.8
S3	0.6	1.0	1.0
S4	0.7	1.4	2.5
S5	0.5	1.4	0.7
S6	1.4	1.3	1.4

Figure 7.5: Average trial times for each participant.
Times are broken down by front, right, and top 2D view orientations

Timing data did not vary much with shape. Average times were all between 3.5 and 4.5 seconds, with the exception of shape 10 (the most complex shape), which required an average time of 5.4 seconds. Timing did not correlate well with rated shape complexity ($r = 0.4$). More complex shapes possibly required more time; however, this relationship was not straightforward. Hence, support for hypothesis 7.2 was unclear.

Timing data also did not correlate with trial number. In other words, there did not seem to be a downward trend (learning effect) or upward trend (fatigue) over the 30 trials. Furthermore, some participants reported that they did not realize they had seen the shapes more than once.

2.4.3 Self-Reports of Task Difficulty

Two participants rated top views the most difficult, two rated right views most difficult, one rated front and right most difficult, and one rated all views equally. These ratings did not always correlate with the timing data. For example, participant 4 rated top views the easiest but required the most time with them (see Figure 7.5). Despite the wide range in ratings, top views required the longest time for most participants, with the exception of participants 1 and 6. Participant 6 reported difficulty distinguishing between left and right, which likely explains why top views were easiest for this participant.

2.4.4 Errors

Only one error occurred. It was on a top view of model 5 (the second most complex shape). The correct letter was in a corner and the participant picked a letter from a different corner, indicating that the view was mentally rotated the wrong way. This agrees with the ideas that the task is more difficult with top views and complex shapes. However, it is also possible that the mistake was simply a slip.

2.4.5 Other Observations

Participants commented that the task was challenging and fun. Some participants commented that they felt nervous or intimidated with the experimenter watching. It is likely that the task seemed like it should be easier than it actually was, so participants were embarrassed about taking a long time or choosing the wrong answer in front of the experimenter.

Support for hypotheses:

H7.1. Shapes rated as more complex would require more time, but errors would not be affected.

This hypothesis was not supported. The relationship between shape complexity and task difficulty was not straightforward.

H7.2. View orientation would not affect task time or errors.

This hypothesis was not supported. Top views appeared to require more time than front and right views.

2.5 Conclusions

- 2D view orientation appeared to affect time required for the mental registration task. For most people, top views took the longest.
- There was no clear relationship between object complexity and difficulty of the mental registration task. However, very complex geometry seemed to increase task time, especially when complex geometry was partially hidden.
- There did not appear to be learning or fatigue effects with 30 trials (10 shapes shown 3 times).
- People who have difficulty distinguishing left and right could have difficulty with front and right views in this type of display.

3 Mental Registration Study

Two experiments compared 2D/3D mental registration difficulty for different display types. Experiment 1A considered 2D orthographic projections and Experiment 1B considered 2D slices.

3.1 Design

Independent variables were display type (orientation icon, in-place cutting plane, or ExoVis) and 2D view orientation (parallel to the top, right, or front of the object). Dependent variables were time, accuracy, and subjective ratings of difficulty.

Experiment 1A used a 2 x 3 within-subjects' design (2 display types x 3 view orientations), with the addition of a control condition that did not have various view orientations. Experiment 1B used a 3 x 3 within-subjects' design (3 display types x 3 view orientations), with the addition of a control condition that did not have various view orientations. Figure 7.6 illustrates the experimental conditions.

Orthographic view experiment

	2D view orientation		
	T	R	F
Control task			
ExoVis			
Orientation Icon			

Slice view experiment

	2D view orientation		
	T	R	F
Control task			
Cutting plane			
ExoVis			
Orientation Icon			

Figure 7.6: Experimental conditions for Experiment 1

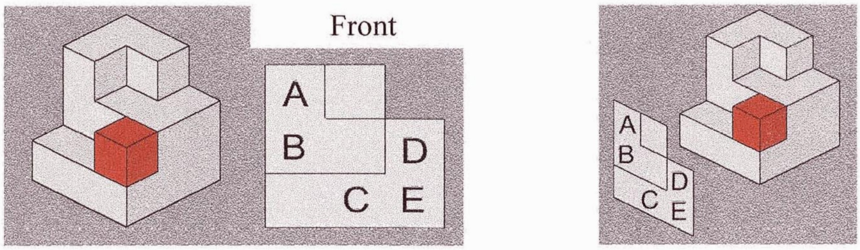
Participants completed ten repetitions of each experimental condition and 30 repetitions of the control condition. Trials were grouped by display type. To prevent order effects, order of the displays was counterbalanced using a Latin Squares design, and an equal number of males and females participated in each order. Orientations were in pseudo-random order to prevent participants from simply remembering the spatial relationship between 2D and 3D views from one trial to the next.

3.2 Method

Experimental setup and procedure were similar to the preliminary study. Differences are described in the remainder of this section.

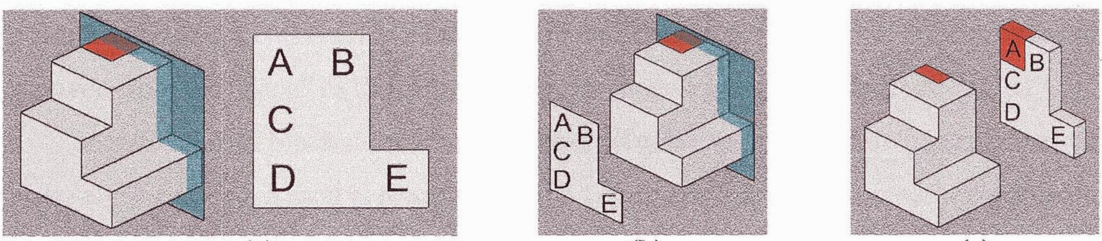
3.2.1 Tasks

The 3D view and 2D view were combined using cutting planes, ExoVis, or orientation icon methods. Example tasks from the orthographic and slice view experiments are shown in Figure 7.7 and Figure 7.8 respectively.



(a) **(b)**

Figure 7.7: Sample tasks: orthographic view experiment.
Participants identify the letter corresponding to the red block. The correct answer is D.
(a) Orientation icon display, (b) ExoVis display.



(a) **(b)** **(c)**

Figure 7.8: Sample tasks: slice view experiment.
Participants identify the letter corresponding to the red block. The correct answer is A.
(a) Orientation icon display, (b) ExoVis display, (c) In-place display.

3.2.2 Control Tasks

A control task was designed to estimate time required for non-registration parts of the task (i.e., moving the mouse and choosing an answer). Participants observed two 3D views of a block shape. One view contained one red cube and the other view had unique letters on five of the cubes (see Figure 7.9). Participants identified the letter corresponding to the red block. This control task measured the time and difficulty of doing an identification task without mentally registering 2D and 3D views. It therefore provided a baseline. The control task was included in both experiments to allow results of the two experiments to be compared. Participants were expected to perform similarly on control trials and in-place trials in the slice experiment, since neither task requires 2D/3D mental registration.

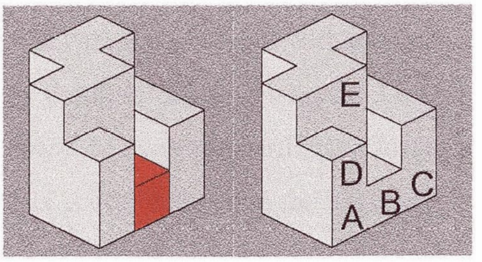


Figure 7.9: Sample control task.
Participants identify the letter corresponding to the red block. The correct answer is B.

3.2.3 Stimuli

Because complex, hidden geometry seemed to make the task more difficult in the preliminary study, a constraint was added to reduce these types of shapes. Blocks were not removed from the "back" of the object where the shape's geometry would be hidden.

A total of 34 block shapes were created. 30 of these were used in the experimental trials. The other 4 were used in practice trials and documentation. In the experimental trials, participants saw each block shape 3 times (experiment 1A) or 4 times (experiment 1B), but never more than once with the same 2D view orientation (front, right, or top). Each shape was shown exactly once with each display type so that the collection of shapes would not be a confounding variable.

Stimuli were presented as static images. For orientation icon trials of orthographic views, the 2D view orientation was given in a text label centred above the 2D view, as in Figure 7.7 (a). In all other trials, the 2D view orientation could be inferred from the orientation of the placeholder or the 2D view itself.

3.2.4 Participants

Participants were recruited from various levels of the computer science student population (from first year to graduate level) at Simon Fraser University. Each participant was randomly assigned to one of the two experiments.

Experiment 1A (Orthographic Views): 12 university students (6 male and 6 female) participated. Participants had varied experience with computer graphics. Ten participants were in the age group 19-25 and two were 26-35.

Experiment 1B (Slice Views): 16 university students (8 male and 8 female) participated. Participants had varied experience with computer graphics. Eleven participants were in the age group 19-25, four were 26-35, and one was 36-45. Data from one participant was incomplete because the participant forgot to complete one part of the study. This participant's data is not included in the analysis.

3.2.5 Procedure

The procedure for each condition was as follows:

- Review instructional materials that explain the views that will be used in that condition. Review example trials with correct answers. Resolve any confusion about the task.
- Complete nine practice trials, with help if necessary.
- Complete thirty experimental trials.

The experimenter helped the participant through the first practice session to ensure the participant understood the task and how to operate the software. The participant was then left alone to complete the remaining tasks (because participants in the preliminary study felt nervous and uncomfortable when they were observed). In the post-trial questionnaire (see Appendix 2), participants rated the difficulty of performing the study task with each display type and view orientation.

3.3 Hypotheses

H7.3. Mental registration would be easier with more integrated views. That is, the best performance was expected with in-place, second best with ExoVis, and worst with OI.

H7.4. With the OI display, mental registration would be more difficult for top views than for front and right views (because a larger mental rotation [47] would be required). With ExoVis and in-place displays, mental registration difficulty would be the same for all view orientations.

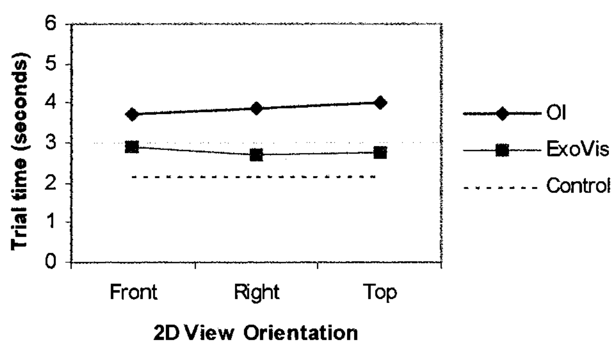
3.4 Results

This section summarizes the results of experiment 1. More detailed statistical tables may be found in Appendix 3.

3.4.1 Timing Data

Figures 7.10 and 7.11 show average times to complete the trial task in the orthographic projection and slice view experiments. The results (see details below the figures), show that mental registration is significantly more time consuming with orientation icon (OI) displays than with ExoVis displays, and is fastest with in-place displays and the control task.

Orthographic Projection Experiment



Standard Deviations

	Front	*Right*	*Top*
OI	1.5	1.7	2.4
ExoVis	2.4	1.1	1.1
Control	0.8		

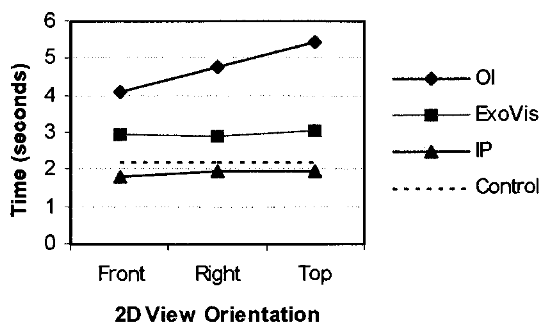
Figure 7.10: Average trial times for the orthographic view experiment.
OI = Orientation Icon.

The data was transformed using a natural logarithm (to improve its fit to a normal curve) and analyzed using 2 X 3 repeated measures ANOVA to compare OI and ExoVis displays with three orientations. The sphericity assumption was met. ANOVA showed a significant main effect for display type ($F(1, 11) = 49.0, p < 0.001, \eta_p^2 = 0.817$); hence, OI and ExoVis displays were significantly different, supporting hypothesis 7.3. Orientation ($F(2, 22) = 0.3, p = 0.776, \eta_p^2 = 0.023$) and interaction between orientation and display ($F(2, 22) = 0.2, p = 0.782, \eta_p^2 = 0.022$) were not significant, contradicting hypothesis 7.4.

Bonferroni-corrected ($p < 0.025$) paired-samples t-tests showed significant differences between OI and control tasks ($t = 9.8$, $df = 11$, $p < 0.001$) and ExoVis and control tasks ($t = 3.6$, $df = 11$, $p = 0.004$).

Slice View Experiment

As shown in Figure 7.11, the slice view task took the most time with OI, moderate with ExoVis, and least with in-place displays. Task time varied with view orientation only for the OI condition.



Standard Deviations

	Front	*Right*	*Top*
OI	1.9	3.0	3.2
ExoVis	1.8	1.3	1.4
IP	0.8	1.2	1.4
Control	0.5		

Figure 7.11: Average times for the slice experiment.
OI = Orientation Icon, IP = In-place.

The data was transformed using a natural logarithm (to improve its fit to a normal curve) and then analyzed using 3 X 3 repeated measures ANOVA (with the Huynh-Feldt correction) to compare orientation icon, ExoVis, and in-place displays with three view orientations. ANOVA found significant main effects for display type ($F(1.68, 23.53) = 44.1$, $p < 0.001$, $\eta_p^2 = 0.759$) and orientation ($F(2, 28) = 11.9$, $p < 0.001$, $\eta_p^2 = 0.46$), and an interaction between display type and orientation ($F(3.75, 52.5) = 6.1$, $p = 0.001$, $\eta_p^2 = 0.303$). Pairwise comparisons showed that all display types were significantly different from each other ($p \leq 0.001$). The top orientation took significantly longer than the front ($p = 0.001$).

Bonferroni-corrected ($p < 0.01$) paired-samples t-tests showed that orientation icon ($t = 10.3$, $df = 14$, $p < 0.001$) and ExoVis ($t = 5.1$, $df = 14$, $p < 0.001$) were significantly different from the control. In-place was not clearly different from the control: although the

p value was small ($t = 2.8$, $df = 14$, $p = 0.013$), the 99% confidence interval for the difference included zero so there may be no difference.

Pairwise comparisons showed that all displays were significantly different from each other for all view orientations ($p \leq 0.001$), supporting hypothesis 7.3. Front and top orientations were significantly different for the orientation icon display ($p = 0.001$) but not for ExoVis or in-place displays. In other words, time to complete the task varied with view orientation in the orientation icon case, but was relatively constant with ExoVis and in-place. This trend can be clearly seen in Figure 7.11, and supports hypothesis 7.4.

3.4.2 Errors

Figure 7.12 shows the percent of incorrect answers in the two experiments. ExoVis displays had far fewer errors than orientation icon displays, and completely eliminated errors in top views, where errors were most prevalent. There were no errors for the in-place or control conditions.

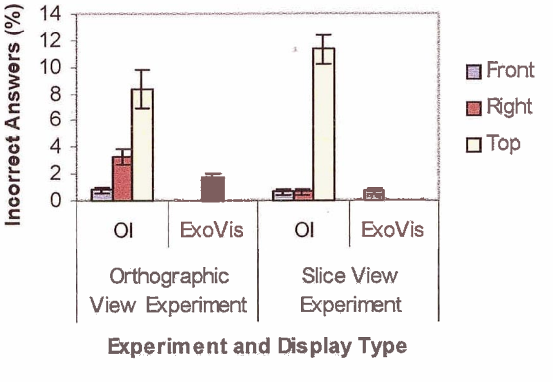
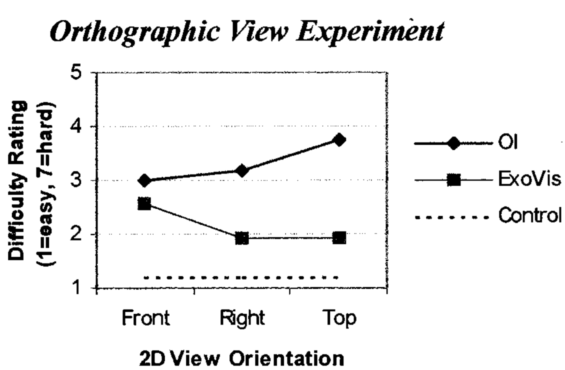


Figure 7.12: Percent of incorrect responses in the two experiments.
Incorrect answers are broken down by display type and 2D view orientation. In-place and control had no errors.

Because the error data was skewed, nonparametric Friedman and Wilcoxon tests were chosen. View orientation was left out of the statistical analysis because the Friedman test only considers one variable (display) and because some display/orientation combinations had few or no errors. Friedman tests showed significant main effects of display in both the orthographic view experiment ($\chi^2 = 13.0$, $df = 2$, $p = 0.002$) and the slice view experiment ($\chi^2 = 25.7$, $df = 3$, $p < 0.001$). In the orthographic view experiment, one-tailed Wilcoxon tests (Bonferroni-corrected; $p < 0.017$) showed a significant difference between OI and control conditions ($Z = 2.6$, $p = 0.005$) and between OI and ExoVis conditions ($Z = 2.2$, $p = 0.013$). ExoVis was not significantly different from the control. In the slice experiment, pairwise one-tailed Wilcoxon tests (Bonferroni-corrected; $p < 0.008$) showed that the OI condition was significantly different from all other conditions ($Z = 2.7$, $p = 0.004$). ExoVis and in-place conditions were not significantly different from each other or the control. These differences support hypothesis 7.3.

3.4.3 Difficulty Ratings

Figures 7.13 and 7.14 show average difficulty ratings for the two experiments. The orientation icon condition was rated more difficult than ExoVis, in-place, and control conditions, supporting hypothesis 7.3. Because the ratings may not necessarily reach an interval level of measurement, nonparametric tests were employed. View orientation was left out of the statistical analysis because the nonparametric Friedman test only considers one variable (display).



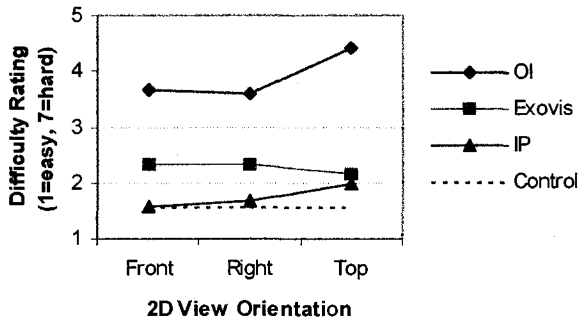
Standard Deviation

	Front	Right	Top
OI	1.6	1.4	1.7
ExoVis	1.5	1.2	1.0
Control	0.6		

Figure 7.13: Average difficulty ratings for the orthographic view experiment.

In the orthographic experiment, the Friedman test showed a significant effect of display ($\chi^2 = 17.3$, $df = 2$, $p < 0.001$). Bonferroni corrected ($p < 0.017$) Wilcoxon tests showed that OI, ExoVis, and the control were all significantly different ($p \leq 0.015$).

Slice View Experiment



Standard Deviation

	Front	*Right*	*Top*
OI	1.875	1.73	1.676
Exovis	1.231	1.303	1.193
IP	1.24	1.155	1.279
Control	0.9		

Figure 7.14: Average difficulty ratings for the slice view experiment.

In the slice view experiment, the Friedman test showed a significant effect of display ($\chi^2 = 26.0$, $df = 3$, $p < 0.001$). Bonferroni corrected ($p < 0.008$) Wilcoxon tests showed that OI was significantly harder than all other displays ($p \leq 0.002$). ExoVis, in-place, and the control were not significantly different from each other.

Support for hypotheses

H7.3. Mental registration would be easier with more integrated views. That is, the best performance was expected with in-place, second best with ExoVis, and worst with OI.

This hypothesis was supported.

H7.4. With the OI display, mental registration would be more difficult for top views than for front and right views (because a larger mental rotation [47] would be required). With ExoVis and in-place displays, mental registration difficulty would be the same for all view orientations.

This hypothesis was supported in the slice view experiment, but not well-supported in the orthographic view experiment.

3.5 Discussion

The data strongly supports hypothesis 7.3. Timing, error, and rating data all agree that mental registration is easier with more integrated views. There is better performance with the in-place display than with ExoVis, and better performance with ExoVis than with the orientation icon. Difficulty ratings also agree with this hypothesis.

Clearly, in-place techniques support the easiest mental registration. However, they are not always appropriate. Clip planes hide large portions of the data and cutting planes can cut the 3D view into many pieces, making analysis difficult. A "planar brush" [70] through a semi-transparent surface avoids cutting, but the 2D and 3D views overlap and occlude each other. ExoVis and OI techniques avoid these problems because views are separated. Thus, views can be moved, adjusted, and managed so they do not interfere with each other.

This experiment indicates that ExoVis may be a good choice when in-place techniques cannot be used. Since the mental registration task with OI displays took significantly longer than with ExoVis displays, orientation icons should only be used when specifically required. Examples might be for non-oblique viewing of 2D views (e.g., for judging whether lines are parallel) or to display a very large number of 2D views (since occlusion could then become a problem with ExoVis).

Support for hypothesis 7.4 is less clear. Timing in the slice experiment (and to some extent difficulty ratings in both experiments) indicate that mental registration with OI displays was most difficult with top views. With ExoVis and in-place displays, times and difficulty ratings did not vary significantly with view orientation. This difference can be explained if mental rotation is used to align the 2D and 3D views. In the OI condition, a larger mental rotation is required for top views than for front or right views, but with ExoVis, no mental rotation is needed. In addition, some participants commented that with OI top views they could not remember whether to rotate the view left or right. Although it was not significant, front views were rated most difficult for orthographic ExoVis displays. The reason for this is unclear. It is possible that it is an artifact of the questionnaire; the example given for that condition may have been particularly difficult. On the other hand, this result may merit further investigation.

Comments by participants indicate that they used two different strategies to complete the tasks: (1) a mental rotation strategy: the views were mentally rotated until they were aligned with one another and (2) a pattern matching strategy: unique features in one view were matched with features in the other. Participants likely combined these two strategies, as suggested by Osborn and Agogino [38]. Mental rotation will always work if you can remember which way to rotate the view but feature matching can fail when there is symmetry in the 2D view. Feature matching may be easier with orthographic views than with slices because there are inner contour lines. It is therefore possible that a feature matching strategy was preferentially used for this condition. This could explain why there was no significant difference in timing between view orientations for the orthographic view experiment. Future experiments could verify this hypothesis.

Error analysis further supports the idea that two strategies were used. Most errors in OI displays appeared to be caused by mentally rotating the view in the wrong direction, mistaking the view orientation for a different orientation, or choosing the wrong side of a symmetric 2D view. ExoVis displays eliminated these common errors, leaving only occasional side-by-side errors (choosing a letter next to the correct letter on the 2D view).

In the slice experiment, results for the in-place and control conditions were very similar, as expected. However, some participants found the in-place display condition confusing because the task seemed too easy. Although the difference was not significant, this confusion may explain why the in-place condition was rated slightly more difficult than the control condition.

As a caveat, notice that the experiment always used orthographic (isometric) projection to project graphic scenes to the computer screen. Other types of projection (e.g., perspective) may yield slightly different results and could be interesting to study.

4 Conclusions

This experiment establishes that mentally registering 2D and 3D views is easiest with in-place displays, hardest with orientation icons, and in-between for ExoVis. There is also an interaction between display type and 2D view orientation, such that difficulty sometimes varies with 2D view orientation for orientation icons, but stays relatively constant for in-place and ExoVis displays.

Although these differences are now clear, we should not assume that in-place displays are always best and orientation icon displays are worst. This experiment tested a low-level mental registration task. Real visualization tasks require mental registration (when both 2D and 3D views are used), but also include many other mental and physical operations (search, navigation, measurement, hypothesis testing, etc.). Therefore, ease of mental registration is not the only important property of a display. Other important properties may include low occlusion levels and display flexibility, attributes somewhat lacking in in-place displays. The next step is to find more complex visualization tasks for which 2D and 3D displays are both useful, and then match those tasks to the most appropriate display types via further user studies. Some such studies are described in the following chapters.

Chapter 8: Experiment 2 - Orientation & Position

The description of Experiment 2B and timing and accuracy results from that experiment were published in the *ACM Conference on Human Factors in Computing Systems (CHI)*.

1 Overview and Objectives

This chapter describes two experiments that compared 2D, 3D, and 2D/3D combination methods for orientation and relative positioning tasks:

- Experiment 2A compared three methods for combining three orthogonal 2D views.
- Experiment 2B compared several 2D/3D combination methods to 2D and 3D views alone.

2 Tasks

Orientation and relative position tasks were chosen because they are common in many applications and were expected to benefit from a combination of 2D and 3D views since they require both 3D understanding and precision (see chapter 5).

The tasks were abstract (i.e. simple shapes such as blocks, spheres, tori, and planes) rather than designed for a specific domain (e.g., medical imaging or CAD) to provide generic results that are hopefully applicable to many fields. In addition, these abstract tasks required only simple displays (minimizing conflicting factors), did not require domain knowledge (so finding user study participants was easier), and had clearly defined correct answers.

2.1 Relative Position Task

This task was a variation of St. John *et al.*'s "over different" relative position task [51], and was purely perceptual in nature. Participants used 3D views and/or 2D orthographic views to estimate the position of a ball relative to a block shape (see Figure 8.1). Specifically, they determined which sub-block was directly beneath the ball, estimated the amount of empty space (vertically) between the ball and block shape, and reported the height as their answer.

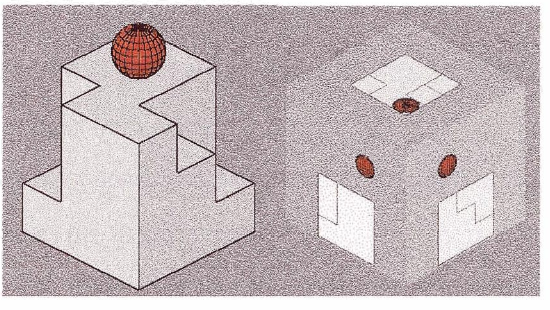


Figure 8.1: Relative position task.
Participants determine the amount of empty space between the ball and block shape.

Several changes were made to St. John *et al.*'s "over different" task. A different block style was used so the number of possible ball positions was constant for all trials. Also, in the St. John task, participants determined which block was directly beneath the ball, and reported their answer by clicking on a separate 3D view. Because a 3D view was available, the "2D" condition was really a 2D/3D combination. Using this reporting method would not allow comparison of a strict 2D condition to a 2D/3D combination. Instead, participants determined which block was directly beneath the ball, estimated the amount of empty space (vertically) between the ball and block shape, and reported this height as their answer. Correctly identifying the height required understanding the ball's position relative to the block shape. This task also involves a truly 3D spatial relationship between the block and ball (rather than simply the 2D layout from a top-down view).

2.1.1 Stimuli

Scenes were modelled in Trispectives Technical v. 2.0. Like Experiment 1 (see chapter 7), block shapes were generated by removing 2, 5, or 8 sub-blocks (size 1 x 1 x 1) from a base shape containing 27 sub-blocks (3 x 3 x 3). An example block shape is shown in Figure 8.1. Removal of sub-blocks was purposely constrained so that all shapes would have similar overall form and complexity. Specifically:

- The resulting object remained as a single connected component and was not allowed to lose its 3 x 3 x 3 structure (i.e., no 3 x 3 slab was completely removed).
- Sub-blocks were removed contiguously from either one or two locations, but not from more than two locations.
- Few sub-blocks were removed from the "back" of the object where the shape's geometry would be hidden.
- Sub-blocks were removed from the top down, and no sub-blocks were removed from the bottom slab.

A red sphere (the "ball") was positioned directly above one of the sub-blocks. The sphere's diameter was the width of a sub-block.

Stimuli were presented as static images. Like St. John *et al.*, 3D views were rendered with orthographic projection to make the figures appear as small objects (e.g., toys) viewed up close. 2D views were rendered from the top, right, and front sides of the object (third-angle projection).

2.2 Orientation Task

In the orientation task, participants used a 3 DOF input device to orient a plane relative to a torus, such that the torus was cut into two identical parts (as if slicing a bagel in half). This task was both perceptual and motor in nature. The task was modelled after slicing plane orientation tasks in medical imaging and other volume data applications. For example, medical images of the chest area are usually aligned with the main axes of the body. However, because the heart is at an oblique angle, physicians often need to orient an oblique slice through the region in order to get a useful view. Orientation tasks are also common in other 3D graphics applications such as CAD (e.g., to set the angle of the roof of a house). Graphics for the orientation task were generated using the Visualization Toolkit [46].

2.2.1 Custom input device for the orientation task

Figure 8.2 illustrates the custom input device used for this task. A 6 DOF Polhemus Fastrak device was used to input plane orientation. Position data from the Fastrak was discarded. To improve stimulus/response compatibility between the display and input device, the Polhemus sensor was attached to a square piece of plywood. The orientation of the plywood directly mapped to the orientation of the red plane.

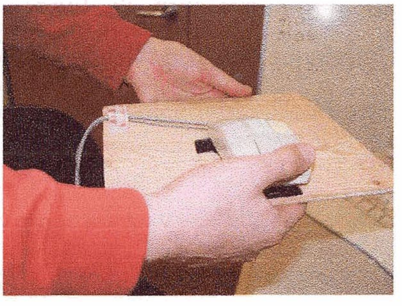


Figure 8.2: Three DOF input device for the orientation task.

With in-place displays, slices can occlude each other, so participants would likely want to turn slices on and off. In addition, participants needed to easily start and end trials. To accomplish this, a 3-button mouse was positioned on the plywood; the three slices could be turned on and off using the three buttons. Mouse buttons were labelled with colours to match the colours of slices on the display. The mouse ball was removed to make room for the Polhemus sensor and make only the buttons functional. Mouse buttons were wired to the same buttons of a 2nd 3-button mouse; the regular mouse was used for ordinary mouse actions while the custom input device recorded mouse clicks.

3 Experiment 2A: Combining Multiple 2D Views

When several 2D slices or orthographic projections are viewed at once, they can be combined on the screen in various ways. Experiment 2A determined how physical integration of several orthogonal 2D views affected performance at relative positioning and orientation tasks. The best of these 2D display techniques was then tested with and without a 3D view in experiment 2B.

The orientation task compared 3 methods for displaying 2D slices (see Figure 8.4):

- *In-place:* views were overlapping in space, unmoved from their original locations. After considering various options by trial-and-error, the slices were made semi-transparent so they did not completely occlude each other.
- *Box:* views were translated from their original locations so they did not overlap. This formed a box shape.
- *Separated:* views were displayed flat on the screen in an L-shape, as if the box view had been cut along one edge and laid flat (3rd angle projection).

The position task compared only box and separated displays because in-place displays do not apply to orthographic projections (see Figure 8.3).

3.1 Design

A 2 x 3 within-subjects design (2 display types x 3 ball heights) was used for the position task and a one-way within-subjects design (with 3 display types) was used for the orientation task. Trials were grouped by task and then by display. Order of the two tasks and the displays within each task were counterbalanced. Ball heights in the position task were ordered pseudorandomly. Participants completed 4 repetitions of each condition in the position task and 6 repetitions of each condition in the orientation task.

Time, accuracy, and subjective difficulty ratings were measured.

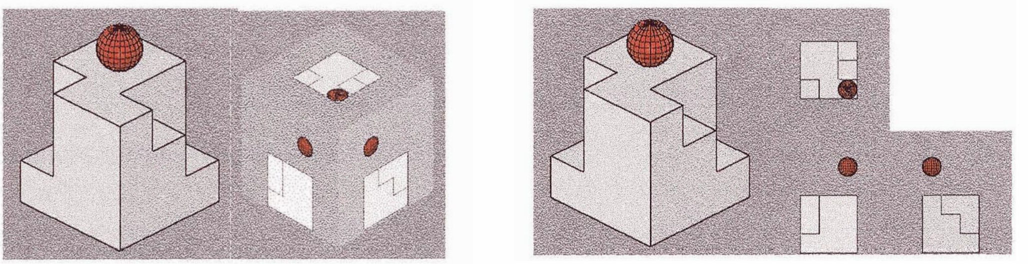
3.2 Method

3.2.1 Participants

Twelve university students in computer science or engineering (9 male, 3 female) took part in the experiment.

3.2.2 Relative Position Task

Example displays for the relative position task are shown in Figure 8.3. The empty space between the block and ball was always 0, 1, or 2 sub-block sized units.



(a) Box display (b) Separated display

Figure 8.3: Displays for the experiment 2A relative position task.
A 3D view was shown with 2D orthographic projections in either (a) a box configuration or (b) a separated configuration. Participants reported the vertical space between the red ball and block. The correct answer for this example is 1.

Orthographic 2D views were rendered from the top, right, and front sides of the object. Box and separated methods for combining these three views (in-place methods do not apply to 2D orthographic projections) were compared. An additional 3D view was shown for both conditions to help participants gain an overall sense of the space and how the 2D views related to each other.

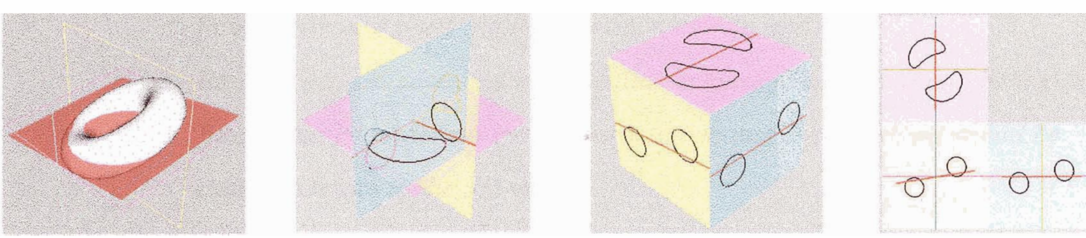
Participants completed 6 practice trials followed by 12 experimental trials (4 with each of the 3 ball heights) for each display. Heights were in pseudo-random order. Display order was counterbalanced. Block shape, ball position, and ball height changed for each trial. The same block shapes were used for each display condition, but ball positions and heights were different to prevent learning effects.

Participants first reviewed instructions that explained the task and views and gave examples with answers. Participants were assisted with practice trials to ensure they understood the task, and then completed the experimental trials on their own.

Participants were instructed to be as accurate as possible. Breaks were permitted only between trials. Trials began when participants pressed a "Ready" button and ended when they clicked a button to report the ball height (see Figure 8.9 under the description of Experiment 2B). No time limit was imposed. Answers could not be changed. In a post-trial questionnaire (see Appendix 2), participants rated task difficulty with each display, gave opinions of the displays, and commented on usefulness of the 2D and 3D views.

3.2.3 Orientation Task

In-place, box, and separated displays were compared (see Figure 8.4). 2D views were slices through the centre of the 3D scene.



(a) 3D view (b) In-place (c) Box (d) Separated

Figure 8.4: Displays for the experiment 2A orientation task.
The 3D view (a) was shown with the in-place (b), box (c), or separated (d) 2D slices. Participants oriented the red plane so it matched the orientation of the torus.

Participants completed 4 practice trials and 6 experimental trials with each display type. Torus orientation changed pseudorandomly for each trial. Orientations were always incorrect in more than one 2D view. All participants completed the same 30 orientations in the same order while display order varied between participants; thus, torus orientations were counterbalanced across display types.

Participants were asked to be as accurate as possible. Breaks were permitted only between trials. Trials started by clicking any button on the input device and ended by clicking any two buttons simultaneously. No time limit was imposed. In a post-trial questionnaire (see Appendix 2), participants rated task difficulty with each display, gave opinions of the displays, and commented on usefulness of the 2D and 3D views.

3.3 Hypotheses

3.3.1 Relative position task

H8.1. Box would be faster than separated.

H8.2. Box and separated would have similar accuracy.

H8.3. Box would be preferred because the 2D views would be easier to relate to the 3D view.

3.3.2 Orientation task

H8.4. In-place would require the most time, have the most errors, and be least preferred. This would occur because overlapping views would be difficult to interpret and users would turn the views on and off.

H8.5. Box and separated would have similar accuracy, but box would be faster.

H8.6. Box would be preferred over separated because the 2D views would be easier to relate to the 3D view.

3.4 Results

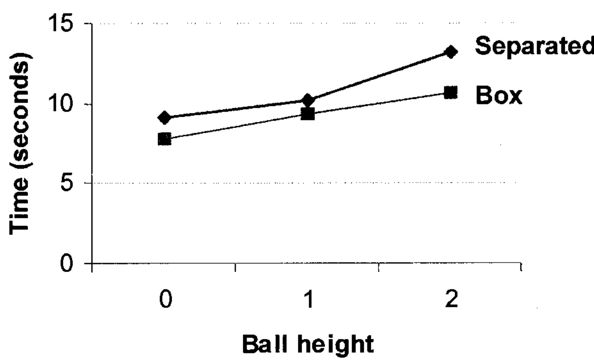
This section summarizes the results of experiment 2A. More detailed statistical tables may be found in Appendix 3.

Unless otherwise specified, timing and error data were analyzed using analysis of variance (ANOVA) followed by pairwise comparisons. When Mauchly's test of sphericity indicated it was necessary, the Huynh-Feldt correction was used. To reduce skew, timing and error data were transformed using a natural logarithm. Rating scale data was analyzed using nonparametric techniques, specifically Friedman tests followed by Bonferroni corrected Wilcoxon Signed Ranks tests.

3.4.1 Relative Position Task

One participant's data was dropped from the analysis because s/he made so many errors that it was unclear whether s/he understood the task. It is interesting to note, however, that this participant made more errors with the separated than with box display even though s/he started with the box display (and therefore had more practice before using the separated display). Among the other participants, only one error was made, so accuracy data could not be analyzed.

Average task time increased significantly with ball height, as shown in Figure 8.5 ($F(1.9,17.6) = 43.5, p < 0.001, \eta_p^2 = 0.829$). All heights were significantly different from each other ($p \leq 0.005$). The separated display took longer on average than the box (as predicted by hypothesis 8.1), but this difference was not significant ($F(1,9) = 1.3, p = 0.281$, $\eta_p^2 = 0.128$).

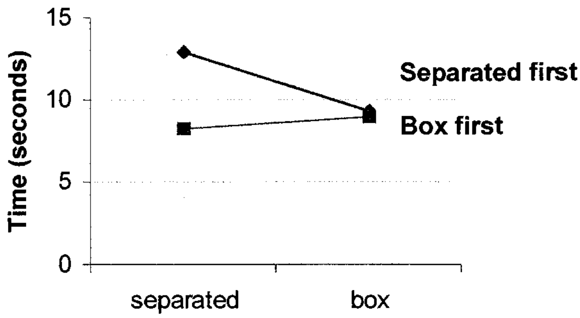


Standard Deviation

Height	*Separated*	*Box*
0.0	8.5	5.8
1.0	8.4	7.5
2.0	10.1	7.0

Figure 8.5: Timing data for each display and ball height.

For average task time, there was also a significant interaction between display and display order ($F(1,9) = 6.6, p = 0.031, \eta_p^2 = 0.422$), as illustrated in Figure 8.6. Participants who started with the box display performed well on both displays, but participants who started with the separated display took significantly longer with that display than with the box ($p = 0.022$). Participants who started with the separated display also varied more in the time required with that display than participants who started with the box display. This uneven learning effect indicates the box display is better for novice users, and also partially explains why the separated display required more time on average overall (even though the difference was not significant).



Standard Deviation

	Separated	*Box*
Sep first	10.8	7.6
Box first	5.3	6.0

Figure 8.6: Timing data for each display and display order.

In addition, the task was rated significantly easier with the box display (Wilcoxon Signed Ranks test: $Z = 2.3, p = 0.021$), as predicted by hypothesis 8.3. As shown in Figure 8.7, average ratings were 2.5 for box and 3.5 for separated, on a scale from 1 (very easy) to 7 (very difficult). Participants commented that the box display made it easier to relate 2D and 3D views, allowed them to perform the task without mental rotation, and helped them from confusing the 2D views with each other.

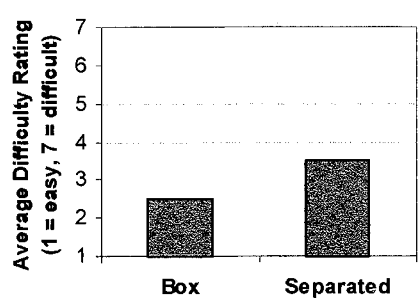


Figure 8.7: Subjective ratings of difficulty with box and separated displays.

However, not all participants preferred the box display; overall, 7 preferred box, 3 preferred separated, and 1 had no preference. One participant who preferred the separated display felt it was "more direct" than the box. This variability among participants suggests we should include both displays as options in any visualization system.

Participants considered both 2D and 3D views to be valuable for the task, indicating that further experiments with 2D/3D combination displays were worthwhile. 3D views were useful for understanding the shape of the block figure, building a 3D mental model of the space, and making an initial guess at the ball position and height. 2D views resolved ambiguity and were therefore useful to determine the precise position and height of the ball.

Support for Hypotheses

H8.1. Box would be faster than separated.

This hypothesis was not supported. Although box was faster on average, the time difference was not significant. However, the uneven learning effect suggests that the box display is faster for novice users.

H8.2. Box and separated would have similar accuracy.

Box and separated had similar accuracy on average, but statistical differences could not be tested because there were very few errors.

H8.3. Box would be preferred because the 2D views would be easier to relate to the 3D view.

This hypothesis was supported (though the reason why box was preferred is speculative).

3.4.2 Orientation Task

Average time, error, and subjective ratings of difficulty for the orientation task are given in Table 8.1. Error values represent the maximum angle between participants' final solution and the correct solution. Error averages include only 7 participants because error values for 4 participants were corrupt and one participant was very inaccurate on all displays and was therefore left out of the error analysis.

Table 8.1: Experiment 2B Orientation Task Results

	Time (s) (n=12)	Error (degrees) (n=7)	Difficulty Rating (1 = easy, 7 = difficult) (n=12)
Separated	24.5 ±16.0	2.0 ± 5.0	3.4 ± 1.0
Box	25.3 ± 19.2	1.9 ± 2.7	3.2 ± 1.3
In-place	23.1 ± 16.8	2.2 ± 3.2	5.7 ± 1.2

There were significant differences between displays only for difficulty ratings (Friedman test: $\chi^2 = 10.6$, $df = 2$, $p = 0.005$). Bonferroni corrected ($p < 0.017$) Wilcoxon Signed Ranks tests showed that in-place was rated significantly more difficult than box and separated displays ($p \leq 0.005$), as predicted by hypothesis 8.4. Furthermore, 10 out of 12 participants rated the in-place display least preferred, and only 1 rated it most preferred. Participants disliked the in-place display because it was too cluttered, forcing them to turn slices on and off. Participants were almost evenly split over whether they most preferred the box (5 participants) or separated display (6 participants). Advantages of the box display were orientation cues that indicated which slice was which and a natural correspondence to input device motion. By contrast, some participants found the separated display more simple and clear, and felt it allowed them to more easily focus on one dimension at a time.

As in the relative position task, participants considered both 2D and 3D displays useful. 3D was used to gain a general understanding of the scene and to orient the plane approximately, while 2D was helpful for fine-tuning. Since both 2D and 3D appeared to be helpful, this idea was tested by comparing 2D/3D combination displays to 2D and 3D displays alone (see experiment 2B). Either the box or separated display could have been selected for further testing; the box display was chosen because it was rated slightly easier (even if not significant) and because this would be consistent with the relative position task.

Support for Hypotheses

H8.4. In-place would require the most time, have the most errors, and be least preferred. This would occur because overlapping views would be difficult to interpret and users would turn the views on and off.

This hypothesis was partially supported. In-place was rated significantly more difficult that the other displays and was least preferred. However, there were no significant differences in time or error results.

H8.5. Box and separated would have similar accuracy, but box would be faster.

This hypothesis was partially supported. No significant differences in timing or accuracy were found, suggesting that box and separated have similar accuracy.

H8.6. Box would be preferred over separated because the 2D views would be easier to relate to the 3D view.

This hypothesis was not supported. Approximately half the participants preferred the box display and half preferred separated. However, those participants who preferred the box display appreciated that it made relating the views easier.

4 Experiment 2B: Combining 2D and 3D Views

Experiment 2A considered different ways of displaying multiple 2D views in an orientation icon 2D/3D combination display. Experiment 2B compared the best of these orientation icon displays to other 2D/3D combinations (ExoVis and in-place) and 2D and 3D displays alone. The same two tasks were studied.

4.1 Design

A between-subjects design was used for display type because learning effects were observed in experiment 2A (see Figure 8.6); with five displays, such learning effects could overshadow display differences. Other factors were within-subjects. A 5 x 5 (display x ball height) design for the position task and a 5 x 3 (display x trial type) design for the orientation task were used. Note that there were several design differences from experiment 2A:

- Between-subjects design (instead of within-subjects).
- Five displays were compared and all but one of these displays differed from displays in experiment 2A.
- Five ball heights in the position task (compared to 3 in experiment 2A).
- Trial type (orientation of the torus relative to the view vector) was considered in the orientation task analysis. Note that trial type was a post-hoc analysis and was not built into the experimental design.

Each participant completed both tasks with one type of display. Task order was counterbalanced. Time, accuracy, and subjective difficulty ratings were measured. For each trial, participants also rated their confidence in their answers (for the position task) or estimated their error (for the orientation task).

4.2 Method

Forty university students (20 male, 20 female) took part in the experiment.

4.2.1 Relative position task

Five displays were compared, as described below and shown in Figure 8.8:

1. ***2D:*** orthographic projections from the top, front, and right. These were arranged in a box shape so that their orientation matched the direction of projection.
2. ***3D rotated:*** two 3D views, rotated 90° relative to one another (similar to St. John *et al.*'s [51] "3D" condition).
3. ***3D shadow:*** a 3D view with a directional light centred above the scene, so a shadow of the ball projected directly downwards onto the block beneath it.
4. ***ExoVis:*** 3D view with 2D projections surrounding it.
5. ***Orientation icon (OI):*** side-by-side 3D and 2D views. 2D views were arranged as in the 2D condition. This is the closest condition to St. John *et al.*'s "2D" condition (but their 2D views were not arranged in a box shape).

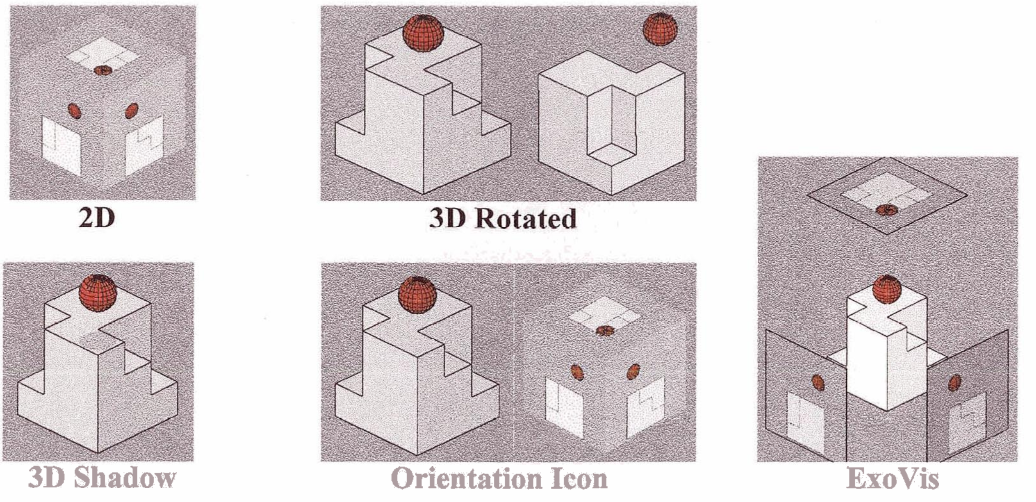


Figure 8.8: Displays for the experiment 2B relative position task.

The procedure and task were the same as experiment 2A, with the following exceptions. Because participants in experiment 2A were very good at estimating ball height, the task was made more difficult by allowing half unit heights. Five answers were possible (0, 0.5, 1, 1.5, or 2). Participants completed 5 practice trials and 20 experimental trials (4 with each of the 5 ball heights) with one of the 5 displays. The same sequence of block/ball scenes was shown for each display, so only the type of view differed. Following each trial, participants rated their confidence in their answer for that trial (on a 7-point rating scale). In a post-trial questionnaire (see Appendix 2), participants gave opinions of the display and rated the difficulty of task components (overall difficulty, mental effort, understanding block shape, understanding which cube the ball was above, and estimating the ball's height). A sample screenshot of the experimental software is shown in Figure 8.9.

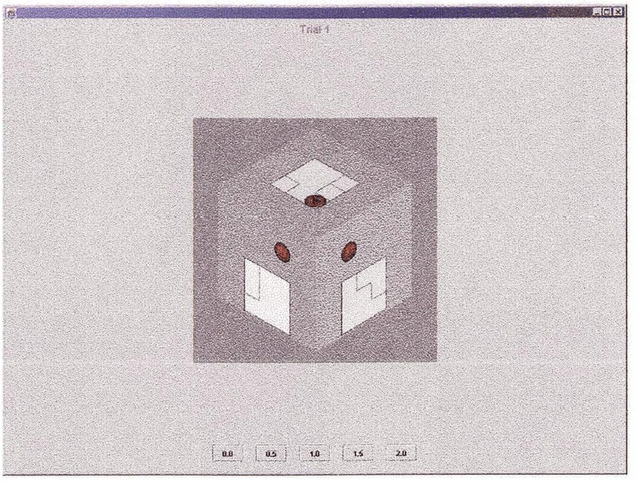


Figure 8.9: Screenshot of the position task experimental software.
Participants press one button at the bottom of the screen to choose their answer. This example shows the setup for Experiment 2B (5 possible answers). Experiment 2A had a similar setup with only 3 possible answers.

4.2.2 Orientation task

Five displays were compared, as described below and shown in Figure 8.10:

1. ***2D:*** slices through the middle of the torus, perpendicular to the three major axes. Slices were arranged in a box shape so their relative orientations were unchanged.
2. ***3D:*** Projection of a 3D scene containing the torus and plane. Orthographic projection was used so the objects appeared as if they were viewed up close.
3. ***Clip Plane:*** 3D view that users could interactively cut through the middle with clipping planes perpendicular to the three major axes. Clip planes removed everything in front of them.
4. ***ExoVis:*** 3D view with 2D slices surrounding it.
5. ***Orientation icon (OI):*** side-by-side 3D and 2D views. 2D views were arranged as in the 2D condition.

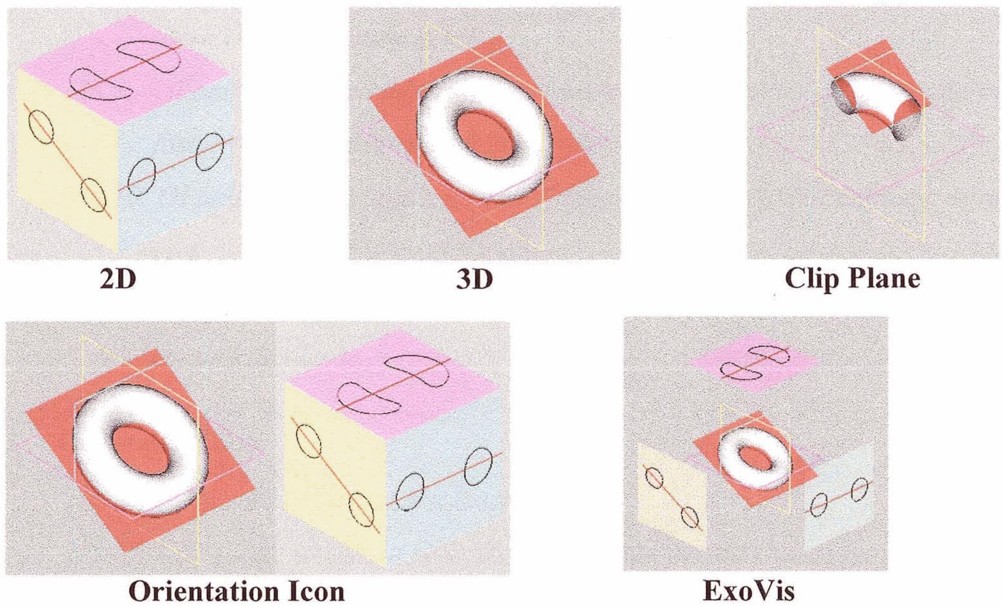


Figure 8.10: Displays for the experiment 2B orientation task.
Approximately correct orientations are shown. Clip plane display shows a torus that has been cut by two orthogonal clip planes (yellow and cyan).

The procedure was the same as experiment 2A, with the following exceptions. Because participants in experiment 2A found some orientations very awkward with the input device, orientations were constrained to be less than 56° from horizontal; this angle was determined by trial and error. The series of torus orientations was identical for all participants. Participants completed 5 practice trials and 16 experimental trials. Because participants in experiment 2A occasionally had trouble clicking two buttons at once, trials were ended by double-clicking. After each trial, participants estimated their error (in degrees) and typed this number at a prompt. In a post-trial questionnaire (see Appendix 2), participants rated the difficulty of task components and gave opinions of the display.

4.3 Hypotheses

4.3.1 Relative Position Task

H8.7. 2D would be faster and more accurate than 3D rotated. (This is a replication of the results of St. John et al.[51]).

H8.8. *3D shadow would be fastest, but estimating height would be difficult so there would be many errors.*

H8.9. *OI and ExoVis would have fewer errors than all other displays and be faster than 3D rotated and 2D displays.*

H8.10. *OI and ExoVis would evoke the highest confidence that answers were correct.*

H8.11. *OI, ExoVis, and 3D shadow displays would be liked better than 2D and 3D rotated displays.*

4.3.2 Orientation Task

H8.12. *3D would be fastest but least accurate.*

H8.13. *Clip plane would be slow and inaccurate because users would switch slices on and off to reduce occlusion.*

H8.14. *2D, OI, and ExoVis displays would be equally accurate, but OI and ExoVis displays would be faster since 3D supports approximate navigation.*

H8.15. *2D display users would predict they were less accurate than they actually were (because they would not have a good understanding of the scene and would therefore not be confident in their answers). Other display users would accurately predict their own accuracy.*

H8.16. *OI, ExoVis, and 3D would be liked better than 2D and clip plane displays.*

4.4 Results

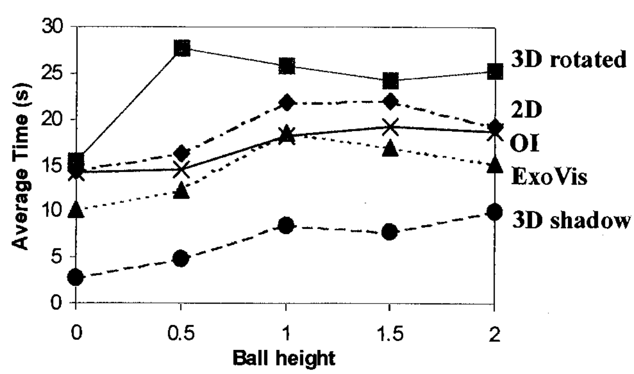
This section summarizes the results of experiment 2B. More detailed statistical tables may be found in Appendix 3.

Unless otherwise specified, quantitative (interval data) results were analyzed using ANOVA followed by pairwise comparisons (for within-subjects' variables) or Tukey HSD post-hoc tests (for between subjects' variables). To reduce skew, timing and error data were transformed (square root for position task errors and natural logarithm for timing data and orientation task errors). Rating scale results were analyzed using Kruskal-Wallis tests followed by Bonferroni corrected Mann-Whitney tests.

4.4.1 Relative Position Task

Timing and total error data were analyzed by 5 x 5 (ball height x display) ANOVA. Average trial time is shown in Figure 8.11. ANOVA found significant main effects for height ($F(4,140) = 21.9, p < 0.001, \eta_p^2 = 0.385$) and display ($F(4,35) = 8.3, p < 0.001, \eta_p^2 = 0.485$) and a significant interaction between height and display ($F(16,140) = 2.5, p = 0.002, \eta_p^2 = 0.225$). Notice that both the F value and η_p^2 value are rather low for the interaction, indicating that the interaction effect is small and the significant result probably occurs partially because of the large number of samples. Thus, display and height effects are likely relatively independent. On average, 3D shadow was significantly faster than all other displays ($p < 0.015$), as predicted by hypothesis 8.8. 2D, 3D rotated, ExoVis, and OI were not significantly different, contradicting hypotheses 8.7 and 8.9. On average, height 0.0 was significantly faster than all other heights ($p < 0.003$), and height 0.5 was faster than heights 1.0 and 2.0 ($p < 0.01$).

Position Task Timing Data



Standard Deviation

Height	*2D*	*3D Rotated*	*ExoVis*	*OI*	*3D Shadow*
0	13	13	6	13	1
0.5	12	28	7	10	3
1	16	19	14	12	9
1.5	21	20	15	12	4
2	16	22	12	12	5

Figure 8.11: Timing data for the experiment 2B relative position task.

Details of the display * height interaction follow. At heights 0.0 and 0.5, 3D shadow was significantly faster than all other displays ($p \leq 0.016$). At heights 1.0 and 1.5, 3D shadow was significantly faster than 2D and 3D rotated displays ($p \leq 0.029$). At height 2.0, 3D shadow was significantly faster than 3D rotated ($p = 0.036$). For the 2D display, height 0.0 was significantly different from height 1.0 ($p = 0.039$). For 3D rotated, height 0.0 was significantly different from all other heights except 1.5 ($p \leq 0.036$). For ExoVis, height 1.0 was significantly different from heights 0.0 ($p = 0.017$) and 0.5 ($p = 0.04$). For 3D shadow, height 0.0 was significantly different from all other heights ($p \leq 0.021$) and height 0.5 was significantly different from heights 1.0 ($p = 0.001$) and 2.0 ($p < 0.001$). Heights were not significantly different with the OI display.

Position Task Errors

Total errors (sum over all participants) are given in Figure 8.12. ANOVA found significant main effects for height ($F(3.7,128.5) = 6.27, p < 0.001, \eta_p^2 = 0.152$) and display ($F(4,35) = 5.1, p = 0.002, \eta_p^2 = 0.367$) and a significant interaction between height and display ($F(14.7,128.5) = 3.3, p < 0.001, \eta_p^2 = 0.273$). Notice that the η_p^2 value is much larger for display than for height or the interaction between height and display, indicating that display has the largest effect on errors.

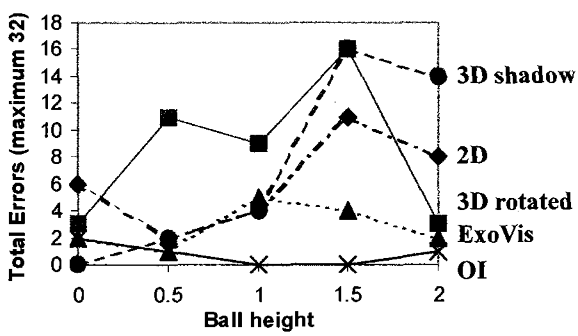


Figure 8.12: Errors for the experiment 2B relative position task.

OI had significantly fewer errors on average than 3D rotated and 3D shadow ($p < 0.041$) and marginally significantly fewer than 2D ($p = 0.056$). ExoVis had significantly fewer errors than 3D rotated ($p = 0.048$). These results support hypotheses 8.8 and 8.9. Height 1.5 had significantly more errors than heights 0 and 0.5 ($p = 0.004$), and marginally significantly more errors than 2.0 ($p = 0.089$). There were no significant differences between displays for height 0.0. At height 0.5, 3D rotated had significantly more errors than all other displays ($p < 0.026$), supporting hypotheses 8.7 and 8.9. At 1.0, 3D rotated had more errors than OI ($p = 0.03$). Displays were most different at height 1.5, where OI was better than 3D rotated and 3D shadow ($p = 0.002$) and marginally significantly better than 2D ($p = 0.062$), and ExoVis was marginally significantly better than 3D rotated and 3D shadow ($p = 0.09$). At height 2.0, OI was significantly better than 3D shadow ($p = 0.035$) and ExoVis was marginally significantly better than 3D shadow ($p = 0.054$).

Figure 8.13 shows average error size (in sub-block-sized units) for each display type. Although 3D shadow had a large number of errors (see Figure 8.12), almost all of these errors (34 out of 36) were incorrect by only 0.5 height units (see Figure 8.13). This indicates that participants understood the ball's position, but slightly misjudged the height. The size of errors for OI and ExoVis tended to be large (see Figure 8.13), but these methods had far fewer errors than the other displays (see Figure 8.12). 2D and 3D rotated displays had both large numbers of errors and fairly large error amounts.

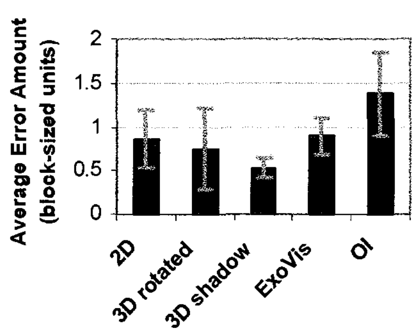


Figure 8.13: Average error size in the experiment 2B position task.
Correct answers (i.e. zero error) are not included in the averages.
Error bars show standard deviation.

Since the number of errors varied for different displays, sample sizes for the error amount measure differed and some samples were very small. Error amount data was therefore analyzed using nonparametric tests because they are more robust than parametric tests with these conditions. The Kruskal-Wallis test showed an overall significant difference between displays ($\chi^2 = 16.0$, $df = 4$, $p = 0.003$). One-tailed Bonferroni corrected

($p < 0.005$) Mann-Whitney tests, corrected for ties, showed that 3D shadow had significantly smaller errors than all other displays ($p \leq 0.005$).

Subjective Ratings

Subjective ratings showed similar trends for all questions. As shown in Figure 8.14, OI and ExoVis were well liked and evoked high confidence that answers were correct. 3D shadow was next best, then 3D rotated, and lastly 2D. The Kruskal-Wallis test showed marginally significant differences between displays for confidence ($\chi^2 = 9.2$, $df = 4$, $p = 0.055$) and significant differences for likeability ($\chi^2 = 17.2$, $df = 4$, $p = 0.002$). One-tailed Bonferroni-corrected ($p < 0.005$) Mann-Whitney tests, corrected for ties, showed that 2D was significantly less likeable than ExoVis ($p = 0.001$) and OI ($p = 0.002$).

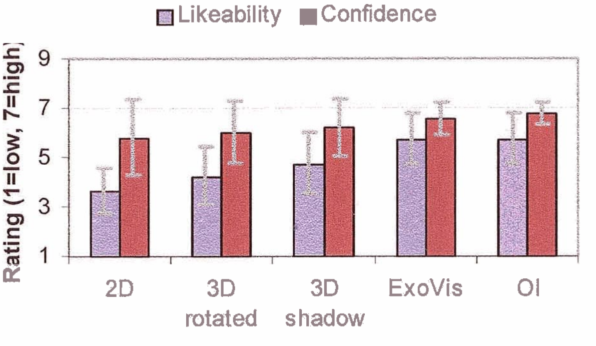
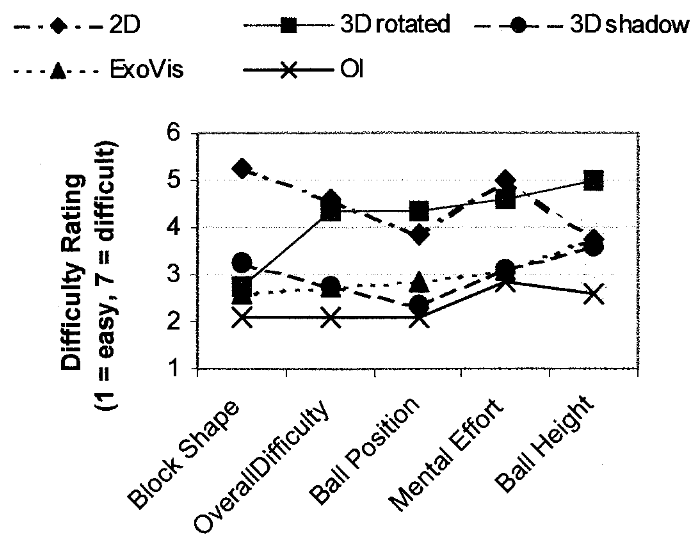


Figure 8.14: Display likeability and inspired confidence for the experiment 2B position task.

Subjective ratings of difficulty are summarized in Figure 8.15. Difficulty trends were similar to confidence and likeability, except that 3D rotated displays were rated quite easy for understanding the block shape, but very difficult for understanding ball position and height.



Standard Deviation

	Overall Difficulty	Mental Effort	Block Shape	Ball Position	Ball Height
2D	2.0	1.7	1.8	1.6	1.8
3D rotated	1.4	1.5	1.5	1.6	1.6
3D shadow	1.3	1.6	1.4	0.7	1.4
ExoVis	1.3	1.6	1.3	1.7	1.6
OI	0.8	1.1	1.1	1.0	1.1

Figure 8.15: Ratings of difficulty for the experiment 2B position task.
ExoVis and 3D rotated are sorted in increasing order.

Kruskal-Wallis tests showed significant differences between displays for overall difficulty ($\chi^2 = 13.4$, $df = 4$, $p = 0.011$), understanding block shape ($\chi^2 = 12.2$, $df = 4$, $p = 0.016$), and understanding ball position ($\chi^2 = 10.4$, $df = 4$, $p = 0.034$). One-tailed Bonferroni-corrected ($p < 0.005$) Mann-Whitney tests, corrected for ties, were used to perform pairwise comparisons. The overall task was significantly more difficult with 2D compared to OI ($p = 0.005$) and with 3D rotated compared to OI ($p = 0.002$). Understanding block shape was significantly more difficult with 2D than with OI ($p = 0.003$) or ExoVis ($p = 0.004$).

As a caveat, note that subjective rating scale results in this study are compared between-subjects. Hence, there is a possibility the differences between displays are a result of differences in how individual participants answered the rating scale questions (e.g., an answer that is considered high by one participant may be considered low by another).

Support for Hypotheses

H8.7. 2D would be faster and more accurate than 3D rotated.

This hypothesis was partially supported. 2D was significantly more accurate than 3D rotated for height 0.5. 2D was also faster on average, but this difference was not significant.

H8.8. 3D shadow would be fastest, but estimating height would be difficult so there would be many errors.

This hypothesis was supported.

H8.9. OI and ExoVis would have fewer errors than all other displays and be faster than 3D rotated and 2D displays.

This hypothesis was partially supported. OI and ExoVis had the fewest errors and were faster on average than 3D rotated and 2D displays. However, the timing difference was not significant.

H8.10. OI and ExoVis would evoke the highest confidence that answers were correct.

This hypothesis was supported by the general trends, but pairwise comparisons for confidence did not show any significant results.

H8.11. OI, ExoVis, and 3D shadow displays would be liked better than 2D and 3D rotated displays.

This hypothesis was supported by the overall trends and the differences were significant for OI and ExoVis compared to 2D displays.

4.4.2 Orientation Task

Based on observations and participants' comments, in the 3D condition, trials where the side of the torus was visible seemed to be easiest. Participants knew the plane was aligned when it became a simple line and/or aligned with the symmetry of the torus. Thus, trials were divided into 3 types: side trials (the torus hole was not visible), top trials (full extent of the hole was visible), and other trials (the hole was partially visible). Examples of these three trial types are shown in Figure 8.16. Note that the three trial types were distributed relatively evenly over the duration of the experiment, so order effects should balance out even though this was not built into the design. Timing and error results were then analyzed by 3 x 5 (trial type x display) ANOVA.

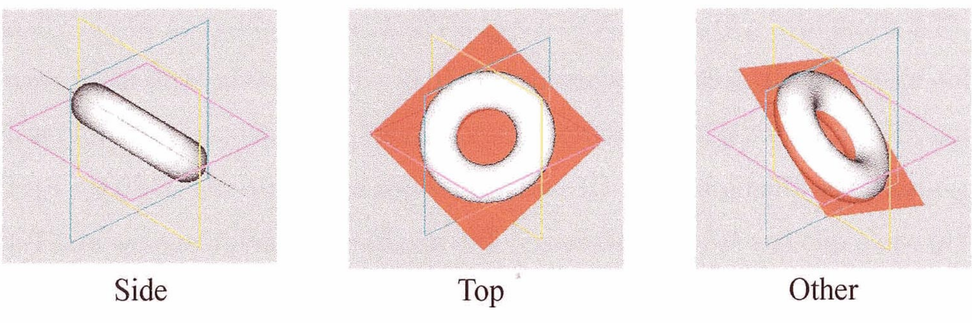
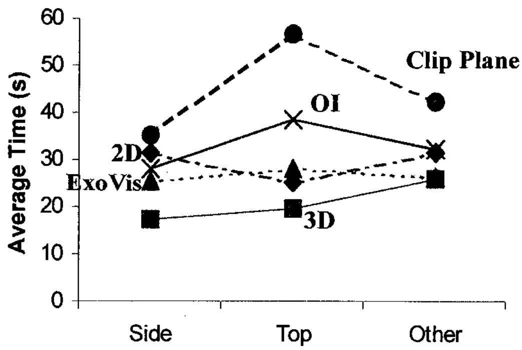


Figure 8.16: Trial types in the experiment 2B orientation task.

Orientation Task Timing Data

Average trial time is summarized in Figure 8.17. ANOVA found significant main effects for trial type ($F(1.9,67.8) = 4.9, p = 0.011, \eta_p^2 = 0.124$) and display ($F(4,35) = 3.9, p = 0.01, \eta_p^2 = 0.308$) and a significant interaction between trial type and display ($F(7.7.67.8) = 4.5, p < 0.001, \eta_p^2 = 0.340$).



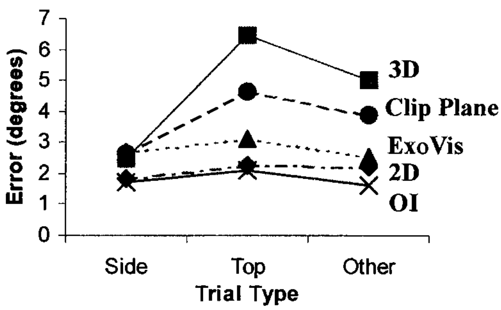
Standard Deviation	Side	Top	Other
2D	19	15	18
3D	9	13	14
ExoVis	20	32	24
OI	14	22	18
Clip plane	22	34	28

Figure 8.17: Timing data for the experiment 2B orientation task.

The clip plane took significantly longer than the 3D display ($p = 0.008$), and marginally significantly longer than ExoVis ($p = 0.059$), supporting hypothesis 8.13. Side trials were faster than other trials ($p = 0.012$). Differences between displays were only significant for top trials, where clip planes took significantly longer than 2D, 3D, and ExoVis ($p < 0.034$). The difference between OI and 3D was marginally significant ($p = 0.052$). There were marginally significant differences between 3D and clip plane ($p = 0.051$) and 3D and 2D ($p = 0.095$) for side trials. These results support hypotheses 8.12 and 8.13, but contradict hypothesis 8.14 (since there was no significant differences among 2D, ExoVis, and OI). For 2D displays, top and other trials were significantly different ($p = 0.046$). For 3D displays, other trials were different from both top and side trials ($p < 0.008$). For clip planes, top trials were different from side and other trials ($p < 0.009$). No significant trial type differences were found for OI or ExoVis displays.

Orientation Task Error

Error data are given in Figure 8.18. ANOVA found significant main effects for trial type ($F(2,70) = 15.4, p < 0.001, \eta_p^2 = 0.305$) and display ($F(4,35) = 7.3, p < 0.001, \eta_p^2 = 0.454$) and a significant interaction between trial type and display ($F(8,70) = 3.6, p = 0.002, \eta_p^2 = 0.291$).



Standard Deviation

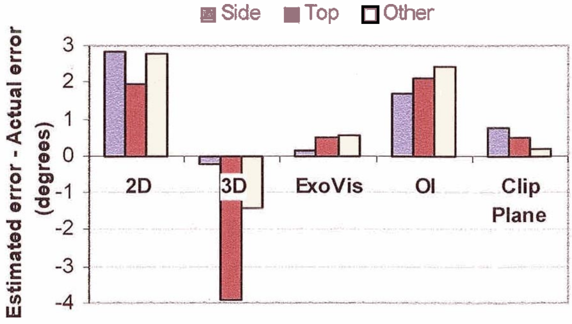
	Side	*Top*	*Other*
3D	2.1	3.8	3.7
Clip plane	2.0	3.7	4.4
ExoVis	1.6	1.9	1.5
2D	1.1	1.6	1.4
OI	1.0	1.2	0.8

Figure 8.18: Error in the experiment 2B orientation task.

The 3D display had significantly more error than 2D and OI ($p < 0.006$), supporting hypothesis 8.12. Clip plane had more error than OI ($p = 0.008$) and marginally significantly more error than 2D ($p = 0.052$), supporting hypothesis 8.13. Side trials had less error than top and other trials ($p < 0.002$). No significant differences between displays were found for side trials, suggesting that 3D can be just as accurate as 2D and combination displays for these trials. However, for top and other trials, 3D displays were significantly worse than all displays except clip planes ($p < 0.05$). Clip planes were worse than OI for other trials ($p = 0.002$) and marginally significantly worse for top trials ($p = 0.069$). Trial types were only significantly different for 3D and clip plane displays. For 3D displays, side trials had significantly less error than all other types ($p < 0.001$), and for clip planes, side trials had less error than top trials ($p = 0.021$) and marginally significantly less error than other trials ($p = 0.075$).

Ability to Predict Error

By subtracting the actual error on each trial from the participant's estimated error (typed at a prompt following each trial), we obtain a measure of how well participants could predict their own accuracy, as summarized in Figure 8.19. For this measure, ANOVA showed significant differences between displays ($F(4, 35) = 2.7, p = 0.045, \eta_p^2 = 0.238$) and trial types ($F(2, 70) = 4.5, p = 0.014, \eta_p^2 = 0.115$) and a significant interaction between display and trial type ($F(8, 70) = 3.8, p = 0.001, \eta_p^2 = 0.301$). Low η_p^2 values for both main effects indicate that the interaction between display and trial type may have a larger effect on ability to predict error than either factor alone.



Standard Deviation

	Side	Top	Other
2D	2.788	2.508	2.854
3D	3.021	4.43	4.723
ExoVis	1.998	2.67	2.226
OI	2.574	2.708	2.277
Clip Plane	4.725	6.797	6.415

Figure 8.19: Ability to predict orientation accuracy.

As shown in Figure 8.19, 2D and OI participants consistently overestimated their error, whereas 3D participants underestimated their error. These results support hypothesis 8.15 for 2D, but contradict the hypothesis for 3D and OI. The results suggest potential problems for 3D displays (because users may be overconfident in their accuracy) as well as 2D and OI displays (because users may take excessive amounts of time before they feel confident in their performance). The problem with 3D displays was likely that participants could not always see changes in plane orientation, depending on the orientation of the camera relative to the torus. For 2D, participants may have overestimated their error because they did not feel confident in their 3D understanding of the scene; however, this does not explain why OI participants had similar results. ExoVis and clip plane participants were best able to predict their own accuracy.

For this measure, there was a significant difference between 3D and 2D (p = 0.041), and a marginally significant difference between 3D and OI (p = 0.079). However, these differences did not exist for all trial types. For top trials, 3D was significantly different from both 2D (p = 0.028) and OI (p = 0.021) and for other trials 3D was marginally significantly different from 2D (p = 0.071). There were no significant differences between displays for side trials, suggesting that people can closely predict orientation accuracy with 3D displays when a good view is available.

Subjective Rating Scale Results

Subjective rating scales did not show significant differences between displays.

Support for Hypotheses

H8.12. 3D would be fastest but least accurate.

This hypothesis was supported.

H8.13. Clip plane would be slow and inaccurate because users would switch slices on and off to reduce occlusion.

This hypothesis was supported.

H8.14. 2D, OI, and ExoVis displays would be equally accurate, but OI and ExoVis displays would be faster since 3D supports approximate navigation.

This hypothesis was partially supported – there were no significant accuracy differences between 2D, OI, and ExoVis, as expected, but times were also not significantly different.

H8.15. 2D display users would predict they were less accurate than they actually were. Other display users would accurately predict their own accuracy.

This hypothesis was partially supported. As expected, 2D display users overestimated their error and ExoVis and clip plane display users predicted their error quite closely. However, OI display users unexpectedly overestimated their error and 3D display users underestimated their error.

H8.16. OI, ExoVis, and 3D would be liked better than 2D and clip plane displays.

This hypothesis was not supported by rating scale results, but was supported qualitatively.

4.5 Discussion

4.5.1 Relative Position Task

Overall, the results indicate that 3D rotated displays are not effective for relative positioning, replicating the results of St. John *et al.* [51]. Based on observations and participants' comments, common problems with this display were difficulties estimating ball height (especially for high heights and 1/2 unit heights) and difficulty relating the 2 views. Four of the eight participants who used the 3D rotated display felt the 2 views sometimes conflicted with one another, even though they knew otherwise. This occurred because the ball position was ambiguous in any one view, and one possible ball position sometimes visually dominated over other possibilities. It is possible that this type of 3D display may be substantially improved by allowing interactive rotation rather than only mental rotation, since relating the views should be easier. However, the time cost associated with rotating the view could be large.

Unlike 3D rotated, the 3D shadow display was very fast and received moderate ratings. Almost all participants who used this display commented that the major difficulty was estimating ball height. Error data also indicated this difficulty. Several participants either requested a ruler or were observed using their hand as a measuring tool, indicating that 3D shadow displays could be very effective for relative positioning with the addition of measurement tools. Alternatively, designers could use a point light instead of a directional light so the shadow size would indicate height. Because estimating height was users' biggest difficulty with this display, likeability, confidence, and ease of use would be expected to increase if measurement cues were added.

Nevertheless, shadows would not always be effective because the light must be placed in a very specific location relative to the objects of interest (e.g., if the light was slightly off to the side the light may be less effective). In addition, shadows can be hard to interpret and costly to render in scenes with complex or dense geometry (e.g., volume data sets). As computing power increases, we can compute, collect, and store larger and larger amounts of data, such that complex and dense information spaces are becoming increasingly common. Thus it is useful to consider 2D displays as an alternative way of resolving position ambiguity. ExoVis and OI had few errors, moderate time, and high ratings on all scales, indicating that combination 2D/3D displays are a better choice than 2D alone for relative positioning tasks and should be chosen when 3D + shadow displays are not practical and/or 3D measurement tools are unavailable.

A fairly small number (8) of participants were in each experimental group in this study. This restriction was necessary for practical reasons: running a large multivariate study with many participants is difficult. Having a smaller number of participants per group allowed the study to include more groups and hence examine a broader scope of variables. However, the small group size also means that differences in spatial ability could be a potential confound in the experiment. To check for this, the groups' previous experience with 3D computer graphics were compared (based on the background questionnaire in Appendix 2). All groups had very similar average experience, except the ExoVis group, which had slightly lower experience. Furthermore, timing data trends were checked after removing outliers (exceptionally slow or fast participants). The only difference was that 2D became slower than 3D rotated. This indicates that the conclusion that 2D/3D combination displays are better than 2D or 3D rotated displays is sound. If anything, with larger groups we might expect better performance with ExoVis and worse performance with 2D displays.

4.5.2 Orientation Task

Participants' comments and the experimenter's observations provided interesting insight into the displays. Most people using the 2D display did not appear to naturally understand how to move the input device to progress towards their goal. Progress was generally made by trial and error, and by focusing on one dimension at a time. Availability of the 3D view produced more directed and coordinated movements.

OI and ExoVis participants tended to move quickly to an approximate solution using the 3D view, and then fine-tune individual dimensions using the slices. Some clip plane participants used a similar strategy, turning off all slices to get an approximate solution, and then using one slice at a time to adjust each dimension. Other clip plane participants started with the default view (2 slices); however, this view was only liked by one participant. It is likely that the others used it only because it did not require changing any settings. Most participants found it difficult to work with more than one clip plane at a time, and found switching between dimensions difficult and annoying, for at least two reasons. First, to switch dimensions users either had to randomly try input device buttons to find the correct one or move their eyes from the screen to the input device to match up the colours. Second, users would often correctly orient the plane in one dimension and then find that this action had altered the orientation in other dimensions.

As for the position task, time and error data were analyzed without outliers in case differences in spatial ability strongly influenced the results. Removing one very slow participant resulted in a faster average time for ExoVis (similar speed to the 3D display). This matches the prediction that ExoVis participants might perform more poorly than other groups because they had less 3D graphics experience. No other changes in timing or error trends were found, indicating that the conclusions reached in this experiment are valid.

5 Conclusions

These experiments suggest that 3D displays with appropriate cues (e.g., shadows) are good for *approximate* orientation and positioning tasks. 3D displays were not useful for *precise* positioning (although this might change if measurement tools were added) or *precise* orientation (except when a good view was available). Clip planes and in-place 2D slices were also not useful for precise orientation, probably because users had to switch back and forth between different slices and could not use several slices at once. Although 2D displays were reasonably effective for precise orientation and relative positioning, users were more comfortable with ExoVis and orientation icon displays. Box orientation icon displays were slightly better than separated orientation icon displays for relative positioning by novice users, but both box and separated displays had advantages and were well-liked by some people.

Chapter 9: Experiment 3 - Qualitative Exploration

1 Overview and Objectives

Experiments 1 and 2 imposed severe limitations on interactivity to carefully control experimental conditions. For example, participants could not rotate 3D views or change 2D slice positions. These restrictions allowed collection of good quantitative data to compare the displays, but restricted the practical value of the results since most real world systems are interactive. In addition, the experiments used abstract data sets (block shapes, spheres, tori, etc.) so the results could be applicable to many domains. However, it was uncertain to what extent the results would be similar for real world data sets and situations.

Experiment 3 was a qualitative exploration that addressed the issues above. Objectives of the experiment were to:

- Compare display types in interactive situations.
- Consider a more specific domain (volume visualization) to see whether the results would be similar to results with abstract data sets.
- Identify important factors that contribute to preferences and usefulness of 2D/ 3D displays.

Results of Experiment 2 (see chapter 8) indicated that both 2D and 3D views were valuable for orientation and relative positioning tasks. However, the results did not show clear quantitative differences between orientation icon and ExoVis 2D/3D combination displays. Hence, in experiment 3 these two displays were compared qualitatively, to try to identify when each display is most useful. The separated OI display was chosen rather than the box OI display to expose participants to the widest possible range of display ideas (including the idea of viewing slices straight-on), to determine which display features were important. This also allowed the experiment to consider whether it would be better to view slices straight-on or at an angle in interactive situations.

2 Design

ExoVis and OI displays were compared (see Figure 9.1 and Figure 9.2). A within-subjects design was used so participants could give opinions of both displays. Order of presentation was counter-balanced. Subjective ratings of preference and difficulty were obtained along with qualitative inquiry results.

3 Method

Participants positioned a green box-shaped "volume of interest" (VOI) around an anomaly in a volume data set. Such VOI tasks are common in 3D imaging; they allow users to study interesting subregions separately from the volume as a whole. A tomato data set was selected so that detailed domain knowledge (e.g., medical knowledge) would not be necessary and university students could be participants.

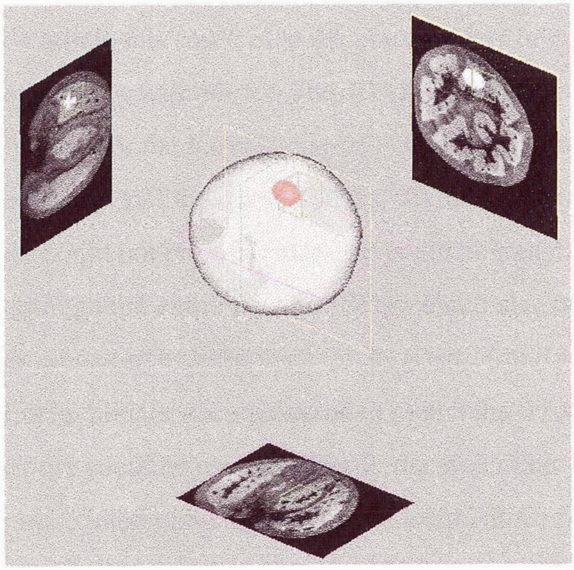


Figure 9.1: ExoVis display for experiment 3.
Placeholders are shown as wireframe planes.

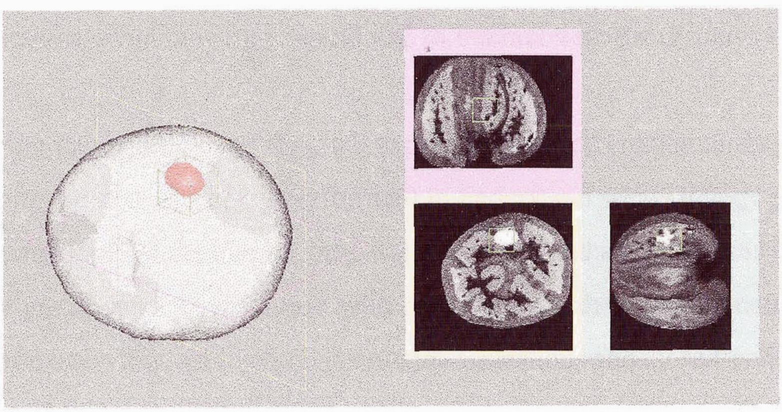


Figure 9.2: Orientation icon display for experiment 3.
Placeholders are shown as wireframe planes.

Each display consisted of a 3D view and three orthogonal 2D slices, as shown in Figures 9.1 and 9.2. The 3D view showed a semi-transparent white isosurface of the outside of the tomato plus a solid red isosurface of the anomaly. Colours were selected to maximize visibility of both isosurfaces, as determined by trial and error. The 3D view also contained 3 "placeholder" planes that indicated slice positions. Each slice was outlined with a unique colour (yellow, cyan, or magenta) and placeholders were assigned the same colour as the slice they represented. Participants could hide the placeholders or change their rendering style (solid, semi-transparent, or wireframe). The 3D view (for the orientation icon display) and the entire ExoVis scene (for the ExoVis display) could be rotated via mouse input. 2D views showed grayscale images of the current slices, where the anomaly appeared as a bright white spot. Slices could not be reoriented, but could be translated back and forth via mouse input to scroll through the entire data set. Slices could also be hidden using check boxes. A green wireframe box represented the VOI. Its position and size in the 3 dimensions could be altered via sliders. Sliders were coloured to match the three slices (yellow, cyan, or magenta) so that colours could be used to identify the slider that would move the green box along a particular axis. Interaction methods were identical for both displays.

Interaction techniques were largely separated from the display to make the interaction consistent and focus on display organization. These interaction methods were not expected to be well liked, but were expected to be sufficient to compare the two displays. Furthermore, participants' discontent with the interaction methods were used to initiate discussions about how they would like to interact with the displays they had experienced.

During the experimental task, the experimenter used contextual inquiry (asking questions while the task was being performed) to understand what strategy participants were using, what parts of the display they were viewing, and any problems they were having. After participants tried the task with both displays, the experimenter conducted a semi-structured interview, asking both open-ended questions and closed-ended rating scale questions regarding how much participants agreed or disagreed with the following statements about each display:

- The display was…
    - Easy to learn
    - Clearly organized
    - Easy to use
- With the display it was easy to…
    - Complete the assigned task

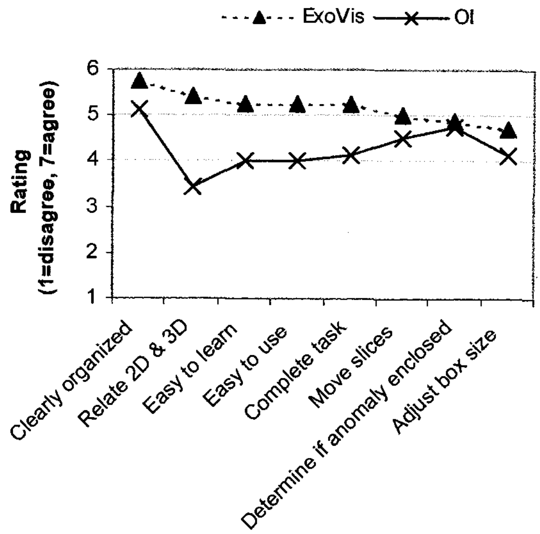
- Relate 2D and 3D views
- Move the slices
- Determine whether the anomaly was enclosed by the box
- Adjust the box size

Interview questions and observation guidelines used by the experimenter may be found in Appendix 2.

Six computer science or engineering graduate students (3 male and 3 female) and two computer science professors (1 male and 1 female) participated in the experiment. Half of the participants had taken part in either experiment 2A or 2B; the others had not taken part in either previous experiment. All participants were previously known to the experimenter and were selected for their strong communication skills, to ensure the interview would be informative.

4 Results

Average rating scale results are shown in Figure 9.3. ExoVis was rated better on average than OI for all rating scale agree/disagree questions. In addition, five out of eight participants said they preferred ExoVis overall. Of the other three, two preferred OI and the other had no preference. Wilcoxon Signed Ranks tests showed that ExoVis was rated significantly easier for relating 2D and 3D views ($Z = 2.3, p = 0.023$), learning ($Z = 2.3, p = 0.023$), and overall use ($Z = 2.1, p = 0.038$). For more detailed statistical tables, see Appendix 3.



Standard Deviation

	ExoVis	*OI*
Clearly organized	0.9	1.1
Relate 2D & 3D	1.5	1.7
Easy to learn	1.2	1.7
Easy to use	1.0	2.1
Complete task	1.5	1.7
Move slices	1.7	1.2
Determine if anomaly enclosed	1.6	1.7
Adjust box size	1.6	1.8

Figure 9.3: Rating scale results, sorted by decreasing average rating for ExoVis.

Participants liked ExoVis because relating the 2D and 3D views was easier. Relying on colours alone (in the orientation icon display) was possible but required more effort. One participant said ExoVis was especially helpful for relating the views when the 3D view was rotated, an important factor in interactive systems. A second major advantage of ExoVis was that people could see all parts of the display at once, so they did not have to move their eyes back and forth between 3D and 2D views. This was especially helpful when translating slices back and forth. In addition, one participant commented that ExoVis was "more natural to use", and a second participant said ExoVis gave a better feeling of control over the actions. The participant who had no display preference claimed that s/he did not use the 3D view. Notice that viewing 2D slices obliquely (in ExoVis) did not appear to be a detriment for this participant.

I observed several different approaches to complete the VOI task, including:

- ***Widest slice strategy:*** first translate the three slices back and forth until each slice shows the largest possible white spot. Then adjust the box position and size so that it encloses the anomaly in these slices.
- ***3D approximation strategy:*** first use the 3D view to get the box in approximately the correct position. Then use the slices for fine-tuning and confirmation.
- ***Slice approximation strategy:*** first translate the slices so they show part of the anomaly. Translate the box to approximately the correct position. Rotate the 3D wireframe view and/or translate the slices to confirm box placement.
- ***3D only strategy:*** Rotate the 3D wireframe view so the camera points directly down one of the major axes. Adjust the box position so it is correct in the other 2 dimensions. Then repeat with the camera pointing down a different axis to complete the task.

Strategies that focused primarily on 2D views (e.g., widest slice strategy) worked quite well with both displays. Strategies that only used the 3D view a little also worked reasonably well (e.g., slice approximation and 3D approximation strategies). However, ExoVis caused serious problems for the 3D only strategy because of occlusion. Specifically, when the camera was positioned so it pointed along a major axis, either the 3D view occluded one of the slices or vice versa, making the task very difficult. The other two slices were seen from the side so they appeared as lines. Seeing slices from the side or from oblique angles was annoying to participants who used both 2D and 3D views and wished to view the slice contents. However, the participant who chose the 3D only strategy actually found the lines helpful because the colours identified which slider would move the box in a particular direction (the placeholders also served this function but the participant found both together useful). This meant that s/he did not want to turn the slices off permanently. At the same time, s/he did not want to manually move slices or turn them on and off every time s/he changed the view orientation, and instead wanted them to move automatically as the camera was moved to reduce occlusion. Such an automated placement algorithm is an interesting topic for future work.

Displaying slices straight on was the main advantage of the OI display and the main disadvantage of ExoVis. Flat slices were considered useful for precise positioning (because of higher resolution and lower distortion) and for comparing more than one data set (because slices could be placed side by side). Three participants suggested that the best display would be ExoVis with an option to view slices straight-on. However, participants disagreed on how to specify when straight-on viewing should be used; some participants wanted to use a mouse click, but others wanted a less intrusive mechanism. One participant suggested having both oblique and non-oblique slices visible simultaneously to reduce the need for mouse clicks; however, this would require extra screen space that may not be available. Hence, future studies are needed to consider the best method of switching between ExoVis slices and non-oblique versions.

One important problem with the OI display was that slices were too far away from the 3D view, so users had to make large eye movements. Slices were organized in an L-shape to represent an open box (like with CAD multi-view projections); however, most participants did not realize this or find it useful. Instead, they suggested placing the slices in a vertical row or surrounding the 3D view (as in the ExoVis display except with slices flat on the screen) to bring them closer to the 3D scene.

Another important factor was interaction technique. Participants wanted direct manipulation for all scene components. Mode buttons (to specify which object was being manipulated) were annoying and distracted users from their task. Hence, the best interaction technique would probably allow users to specify which object to manipulate by simply pointing at the object or a specific part (e.g., an edge). Implementing this type of direct interaction may be more challenging with ExoVis because there are more objects in the scene. Additional research is needed to determine how many objects could be placed in a scene before this interaction technique would no longer be manageable.

5 Conclusions

Experiment 3 identified many factors that influence which display is most appropriate for a task. These factors were ease of relating views, interaction technique, personal strategy, physical proximity of views that were used together, viewing slices from oblique angles, and occlusion. Neither display used in this experiment was ideal for the VOI positioning task, so both require modifications. ExoVis had problems with occlusion and oblique viewing of slices, whereas the orientation icon display was difficult for relating different views and some views were too far apart. A modified ExoVis display may be a good choice for this VOI positioning task, but future work is needed to automatically reduce occlusion as the camera is moved and to allow users to interact directly with slices and view them straight-on without occluding other parts of the scene.

Chapter 10: Discussion

Experiment 1 showed that organizing 2D and 3D views in different ways affects the difficulty of mentally registering 2D and 3D views. Specifically, mental registration was easiest with in-place displays, moderate with ExoVis displays, and most difficult with orientation icon displays. From these results, we might be tempted to naively assume in-place displays are always best and orientation icon displays are always worst. However, Experiments 2 and 3 showed that this was not the case. Participants in Experiment 2B performed very poorly with the in-place (clip plane) display; participants also disliked in-place displays in both experiments 2A and 2B because they had serious occlusion problems. No conclusive quantitative difference between orientation icon and ExoVis displays was found. Qualitative results showed that the best display for a task depended on many factors, such as user preference, strategy, temporal separation of 2D and 3D task components, physical proximity of views, and difficulty of precise judgements with oblique views. (More details of these factors are below.) Mental registration was only one of these many factors, and often not the most important one.

Experiments 2A and 2B (see chapter 8) showed value in combining 2D and 3D views for relative positioning and orientation tasks. 3D views were very useful for building a 3D understanding of the scene and getting an approximate solution, while 2D views were better for precise judgments. Precise judgments with 3D displays were only sometimes possible (e.g., when a good viewpoint was available). Experiment 3 (see chapter 9) agreed with these uses of 2D and 3D views, but also showed the importance of individual variation. For example, some users could perform precise tasks with 3D views alone by using rotation, whereas others found this too confusing and preferred to use 2D views alone or, more commonly, both 2D and 3D together. Allowing more interaction also led to wide variations in task strategy.

Since having both 2D and 3D views can be useful, what is the best way to combine them? The orientation task results indicate that OI and ExoVis methods are better than clip planes, because clip planes force users to physically and cognitively switch between individual slices and a complete 3D view. Hence, for tasks that require integrating information from several slices, clip planes are not appropriate. Clip planes may be more useful when only one slice is needed, when slices can be used sequentially, or when complete slices are unnecessary (e.g., when users can work with a small box cut out of a 3D scene).

Orientation cues provided by ExoVis and OI box methods were valuable, especially while participants were learning the tasks and displays. This was particularly important for novice users with little 3D graphics or CAD experience. Orientation cues were also important for understanding projections (e.g., for the block shapes in the position task), relating the 3 DOF input device to the display in the orientation task, and for rapidly switching attention between 3D and 2D views.

At the same time, viewing slices at an angle was sometimes challenging for precise judgments. This problem was more pronounced with interactive rotation because viewing angles could be very oblique. Interactive rotation also caused occlusion problems with ExoVis. In addition, personal preferences for the displays varied. A system that allows users to switch between ExoVis, OI box, and OI flat displays may resolve these issues. ExoVis may also benefit from an automated placement algorithm that moves objects to reduce occlusion as the view angle changes.

Another important factor was proximity of views that were used simultaneously. For the orientation task, a few participants complained that with ExoVis they could not see more than one 2D slice without moving their eyes. This forced them to use a strategy that focused on one slice at a time. By contrast, for the VOI task, some participants felt ExoVis was better because slices were closer to the 3D view. In this task, many users found they had to frequently look back and forth between 2D and 3D views while adjusting slice positions; this was easier with ExoVis. These observations illustrate the importance of matching the display type to the task and strategy. For many participants, the orientation task was divided into two distinct phases: approximation with the 3D view followed by fine-tuning with the 2D views. Here, OI may be best because it separates the 3D and 2D views to match the strategy. Similarly, ExoVis may be better for tasks that require frequent switching between 3D and 2D views (e.g., to reposition slices and verify the box position in the VOI task).

The "Proximity Compatibility Principle" [16] stated that tasks requiring integration of spatial dimensions (i.e. 3D knowledge) would benefit from 3D displays, whereas tasks requiring focused attention on one or two dimensions would benefit from 2D displays. Directly extending this concept to 2D/3D combination displays would suggest that tasks requiring integrated 3D knowledge or actions would benefit from the more integrated 2D/3D displays (i.e., in-place or ExoVis), and tasks requiring focused attention on one or two dimensions would benefit from more separated displays (i.e., orientation icon or ExoVis). Results of this thesis confirm that this principle has some validity, but at the same time illustrate that it is probably an over-simplification, since many other factors (e.g., personal strategy, precision vs. approximation, and oblique viewing angles) also affected display usability.

Chapter 11: Future Work

This thesis began an investigation into when and how to combine 2D and 3D views. The theories and results presented in the thesis provide a useful starting point, but many avenues of future work are apparent.

1 Enhancements to the ExoVis Technique

Results of experiment 3 indicated that interactively switching between oblique ExoVis 2D views and non-oblique versions would be valuable. Several methods to switch between oblique and non-oblique versions are possible, including:

- Clicking an oblique slice to have it animate so it could be viewed straight-on.
- Mousing-over an oblique slice to have it animate so it could be viewed straight-on.
- Automatically displaying oblique or non-oblique slices depending on the task and/or the user's experience.
- Providing an option to manually switch the entire display back and forth.

Furthermore, oblique and non-oblique views could be displayed either simultaneously (side-by-side) or sequentially. Future user studies could compare these alternatives.

Experiment 3 also showed that occlusion can be a serious problem for ExoVis when interactive rotation is allowed. Manually manipulating objects to reduce occlusion can be time consuming and distract users from their primary goal. An automatic layout algorithm that adjusts positions of walls and callouts based on the current view direction could help to resolve this issue. However, such an algorithm should be under user control so users can switch it off if they have particular positioning requirements (e.g., some objects may be more important than others).

2 Additional User Studies

Future user studies could consider many issues that were beyond the scope of this thesis, including:

- ***Domain-specific experiments.*** For the most part, experiments in this thesis involved generalized tasks so the results could be relevant to more than one application domain. Future experiments could consider more domain-specific tasks and include domain experts as participants, to determine to what extent these general results apply in each domain.
- ***Interactions between tasks, display types, and interaction methods / devices.*** Jacob *et al.* [22] suggest that input devices and techniques should be chosen to match the integrality of the task. This idea likely extends to visualization displays and tasks, and would be an interesting area to explore. For example, we might expect 6 DOF input to work best with 3D displays and tasks that are integrated in 3 dimensions. By contrast, 2D mouse input might work best for 2D displays or tasks that require the use of one or two dimensions at a time.
- ***Discrete and/or non-spatial data.*** Different criteria for selecting 2D, 3D, and 2D/3D combination display techniques may apply to discrete or non-spatial data sets such as 3D scatterplots. Hence the experiments should be repeated for those types of data.
- ***Effects of display type on task strategy.*** Experiments 2 and 3 began to consider different strategies people use to complete tasks, and how different displays affect those strategies. For example, in the orientation task of experiment 2, participants who used the 2D display tended to adjust two dimensions at a time, whereas those who had a 3D view tended to adjust all dimensions simultaneously. However, much more work could be done in this area. Protocol analysis and eye-tracking may help investigate these issues.

- ***Other visualization subtasks.*** In the experiments, a few visualization subtasks (orientation, positioning, and volume-of-interest tasks) were selected. These subtasks were expected to benefit from both 2D and 3D views. Additional studies could consider the other subtasks described in chapter 5. A particular question of interest is whether having both 2D and 3D views visible simultaneously is a detriment for tasks that are expected to be performed best with either 2D or 3D views but not both (i.e. is the extra information distracting?).

Chapter 12: Conclusions

1 Experimental Conclusions

Mental registration of 2D and 3D views was most difficult with orientation icons, moderate with ExoVis, and easiest with in-place displays. However, mental registration was often not the most important factor determining which type of display was best for a given task. 3D displays with appropriate cues (e.g., shadows) were effective for approximate navigation and relative positioning, but precise navigation and positioning were difficult with 3D displays. Appropriate lighting, viewing angle, and measurement tools may alleviate this difficulty in some situations. For precise tasks, orientation icon and ExoVis combination 2D/3D displays were better than 3D displays or 2D displays alone. Compared to 2D displays, combination displays had as good or better performance, inspired higher confidence, and allowed more natural, integrated navigation. Clip plane combination displays were not effective for 3D orientation because it was difficult to use more than one slice at a time and challenging to integrate information from several slices. OI displays with non-oblique 2D views were useful for some precise judgments, whereas OI box and ExoVis displays were better for understanding projections, relating the display to a 3D input device, and for rapidly switching attention between 3D and 2D views. OI displays may be preferred when the task has distinct 2D and 3D phases, and ExoVis may be preferred when 2D and 3D are used closely together.

2 Guidelines for Designers

Based on the theory and experimental results of this thesis, several guidelines are offered to designers of visualization tools for 3D spatial data. The guidelines should be used as a starting point, not as absolute rules. Tasks that are time or safety critical should be carefully tested with all possible displays rather than using these guidelines.

Guidelines for use of 2D and 3D views of 3D spatial data:

- Unless there are occlusion problems, use 3D views alone for understanding or identifying 3D shapes, understanding the layout of objects in a 3D space, approximate 3D navigation / orientation / positioning, and estimating volume.
- Use 2D views for seeing details within a dense space, reading text, estimating area, precise navigation / orientation / positioning, or when only 2 dimensions are needed at a time (e.g., 2D positioning).
- 2D views may be used alone when 3D is not needed for the task (see first point above) and/or the user is very comfortable with the 2D views (e.g., a simple display such as one standard 2D view orientation and/or the user is very experienced with the 2D views). Otherwise, a 3D view should be provided.
- When possible, render shadows and provide measurement tools for relative positioning tasks. When this is not possible, both 3D and 2D views may be needed.
- If in doubt about whether to provide 2D or 3D views, provide both.
- Integrate 2D and 3D views more closely (in-place or ExoVis displays) when the task requires users to go back and forth between them frequently. Use less integrated displays (orientation icon) when the task has distinct 2D and 3D phases.
- Use clip planes only when the task does not require switching frequently between slices or using several slices at once.
- Allow direct manipulation within all views.
- Coordinate the views. When the user changes one view, automatically update all other views. Coordinate 2D and 3D views by providing placeholders and

landmarks. Coordinate 3D views by linking their cameras (e.g., rotation in one view performs the same camera movement in all other views).

- Provide options so users can choose the display that suits their preference and individual work style.

3 Thesis Contributions

This thesis made several research contributions:

- ***Theory and experimental results about 2D/3D combination displays:*** Provided theoretical reasons, quantitative evidence, and qualitative results indicating when and why 2D, 3D, and various 2D/3D combination display techniques are useful. These results should help guide designers to choose the most appropriate display technique for a given task.
- ***ExoVis method:*** Introduced the ExoVis technique for coordinating 2D and 3D views. ExoVis offered better integration between 2D and 3D views than the orientation icon method, and greater flexibility and less occlusion / deformation than in-place techniques.
- ***Methodology:*** Although the thesis used standard evaluation techniques from human-computer interaction, it demonstrated how these methods can be used to evaluate visualization tools. User studies were not previously common in the visualization field and are non-trivial to apply to visualization tasks; hence, this demonstration is a valuable contribution. Furthermore, the thesis summarized (in chapter 3) the challenges of designing systematic, controlled studies in visualization. This summary of challenges is itself a useful contribution.

References

[1] Baldonado, M.Q.W., Woodruff, A., Kuchinsky, A., "Guidelines for Using Multiple Views in Information Visualization", *Proc. of the Working Conference on Advanced Visual Interfaces*, 110 - 119, May 2000.

[2] Bemis S.V., Leeds J.L., Winer, E.A., "Operator Performance as a Function of Type of Display: Conventional Versus Perspective", *Human Factors*, 30 (2): 163-169, Apr. 1988.

[3] Bennett, D. J., "Evidence for a Pre-Match 'Mental Translation' on a Form-Matching Task", *Journal of Vision*, 12(50), 2002.

[4] Blackwell, A.F., Britton, C., Cox, A., Green, T.R.G., Gurr, C., Kadoda, G., Kutar, M. S., Loomes, M., Nehaniv, C.L., Roast, M.P.C., Roes, C., Wong, A., Young, R. M., "Cognitive dimensions of notations: Design tools for cognitive technology", *Proc. of Cognitive Technology*, 325-341, 2001.

[5] Brown, M.A., Slater, M., "Some Experiences with Three-Dimensional Display Design: An Air Traffic Control Visualization", *Proc. of 6th IEEE International Workshop on Robot and Human Communication,* 296 -301, 1997.

[6] Bundesen, C., Larson, A., "Visual Transformation of Size", *Journal of Experimental Psychology: Human Perception and Performance,* 1: 214-220, 1975.

[7] Cabral, B., Cam, N., Foran, J., "Accelerated Volume Rendering and Tomographic Reconstruction Using Texture Mapping Hardware", *Proc. of the 1994 Symposium on Volume Visualization*, 91-97, 131, October 1994.

[8] Card, S. K., Mackinlay, J. D., Shneiderman, B., *Readings in Information Visualization: Using Vision to Think*, Morgan Kaufmann Publishers: San Francisco, 1999.

[9] Carpendale, M. S. T., Cowperthwaite, D. J., Fracchia, F. D., "3-dimensional pliable surfaces: for the effective presentation of visual information", *Proc. of UIST*, 217 - 226, Nov. 1995.

[10] Carpendale, M. S. T., Cowperthwaite, D. J., Tigges, M., Fall, A., Fracchia, F. D., "The tardis: A visual exploration environment for landscape dynamics", In *Visual Data Exploration and Analysis VI,* SPIE vol. 3643, January 1999.

[11] Cowperthwaite, D. J., "Occlusion Resolution Operators for Three-Dimensional Detail-In-Context", Ph.D thesis, Simon Fraser University, Burnaby, British Columbia, 2000.

[12] Delaney, J., *Geographical Information Systems: An Introduction*, Oxford University Press: Melbourne, Australia, 1999.

[13] Ellis, S.R., McGreevy, M.W., "Influence of a perspective cockpit traffic display format on pilot avoidance maneuvers", Proc. of the Human Factors Society 27th An. Meeting, Santa Monica, California, 762-766, 1983.

[14] Goldstein, E.B., "Spatial Layout, Orientation Relative to the Observer, and Perceived Projection in Pictures Viewed at an Angle", *Journal of Experimental Psychology: Human Perception and Performance*, 13: 256-266, 1987.

[15] Grabowski, Ralph, ed., *Using AutoCAD 2000*, Autodesk Press: Albany, New York, 2000.

[16] Haskell, I.D., Wickens, C.D., "Two- and Three-Dimensional Displays for Aviation: A Theoretical and Empirical Comparison", *International Journal of Aviation Psychology*, 3: 87-109, 1993.

[17] Healey, C., "Choosing Effective Colours for Data Visualization", *Proc. of IEEE Visualization*, 1996.

[18] Hollands, J.G., Pierce, B.J., Magee, L.E., "Displaying Information in Two and Three Dimensions", *International Journal of Cognitive Ergonomics*, 2(4): 307-320, 1998.

[19] Houlding, S.W., *Practical Geostatistics: Modeling and Spatial Analysis*, Springer-Verlag: Berlin and Heidelberg, 2000.

[20] Huck, S.W. *Reading Statistics and Research*, 3rd ed. Addison Wesley Longman: New York, 2000.

[21] Interrante, V., "Conveying the 3D Shape of Smoothly Curving Transparent Surfaces via Texture", *IEEE Transactions on Visualization and Computer Graphics*, 3(2): 98-117, April-June 1997.

[22] Jacob, R. J. K., Sibert, L. E., McFarlane, D. C., Mullen, M. P., Jr., "Integrality and separability of input devices" *ACM Transactions on Human Computer Interaction*, 1(1): 3-26, 1994.

[23] Jankun-Kelly, T.J., Ma, K.L., "Visualization Exploration and Encapsulation Via a Spreadsheet-Like Interface", *IEEE Transactions on Visualization and Computer Graphics*, 7(3): 275-287, July/Sept. 2001.

[24] *The Koffka Ring.* See http://web.media.mit.edu/~wad/color/koffka.html or http://persci.mit.edu/people/adelson/publications/gazzan.dir/koffka.html, May 2004.

[25] Kurzion, Y., Yagel, R., "Interactive Space Deformation with Hardware-Assisted Rendering", *IEEE Computer Graphics and Applications*, 17(5): 66-77, 1997.

[26] Lacroute, P., Levoy, M., "Fast Volume Rendering Using a Shear-Warp Factorization of the Viewing Transformation", *Proc. of SIGGRAPH*, 451-458, July 1994.

[27] Levoy, M., "Display of Surfaces from Volume Data", *IEEE Computer Graphics and Applications*, 8(3): 29-37, May 1988.

[28] Litynski, D.M. Grabowski, M. Wallace, W.A., "The Relationship Between Three-Dimensional Imaging and Group Decision Making: An Exploratory Study", *IEEE Transactions on Systems, Man and Cybernetics, Part A: Systems and Humans*, 27(4): 402 - 411, July 1997.

[29] Lorensen, W., Cline, H., "Marching Cubes: A High Resolution 3D Surface Construction Algorithm", *Computer Graphics (SIGGRAPH 1987)*, 21(3): 163-169, 1987.

[30] Laurini, R., Thompson, D., *Fundamentals of Spatial Information Systems*, Academic Press: San Diego, California, 1992, Chapters 1-4, pp. 3-174.

[31] Mack, R.L., and Nielsen, J., "Usability Inspection Methods: Executive Summary", *Readings in Human-Computer Interaction: Toward the Year 2000*, 2nd ed., R.M. Baecker et al., eds., Morgan Kaufmann: San Francisco, 1995, pp. 170-181.

[32] Malzbender, T., "Fourier Volume Rendering", *ACM Transactions on Graphics*, 12 (3): 233-250, July 1993.

[33] Marks, J., Ruml, W., Ryall, K., Seims, J., Shieber, S., Andalman, B., Beardsley, P. A., Freeman, W., Gibson, S., Hodgins, J., Kang, T., Mirtich, B., Pfister, H., "Design Galleries: A General Approach to Setting Parameters for Computer Graphics and Animation", *Proc. of SIGGRAPH*, 389-400, 1997.

[34] McGrenere, J., *The design and evaluation of multiple interfaces: A solution for complex software*, Ph.D Dissertation, Department of Computer Science, University of Toronto, Ontario, 2002.

[35] McGuffin, M.J., Tancau, L., and Balakrishnan, R., "Using Deformations for Browsing Volumetric Data", *Proc. IEEE Visualization*, 401-408, 2003.

[36] Medical Imaging Technology Roadmap Steering Committee, *Image Analysis and Visualization, Report of Working Group 4: Medical Imaging Technology Roadmap*, Industry Canada, 2000, ISBN: 0-662-29130-1.

[37] Moise, A., *Designing Better User Interfaces for Radiology Interpretation*, Ph.D. thesis, Simon Fraser University, 2003.

[38] Osborn, J.R., and Agogino, A.M., "An Interface for Interactive Spatial Reasoning and Visualization", *Proc. CHI*, 75-82, 1992.

[39] Park, S.H., Woldstad, J.C., "Multiple Two-Dimensional Displays as an Alternative to Three-Dimensional Displays in Telerobotic Tasks", *Human Factors*, 42(4): 592-603, 2000.

[40] Patten, J., Ma, K. L., "A graph based interface for representing volume visualization results", *Proc. of Graphics Interface*, 117-124. Canadian Information Processing Society, June 1998.

[41] Perkins, D.N., "Compensating for Distortion in Viewing Pictures Obliquely", *Perception & Psychophysics*, 14(1): 13-18, Aug. 1973.

[42] Pillay, H.K., "Cognitive load and mental rotation: structuring orthographic projection for learning and problem solving", Instructional Science, 22: 91-113, 1994.

[43] Preim, B. and Peitgen, H.-O., "Smart 3D Vizualizations in Clinical Applications", *Proc. Smart Graphics Symposium*, Springer, 343-352, July 2003.

[44] Rosinski, R.R., Farber, J., "Compensation for Viewing Point in the Perception of Pictured Space", In M.A. Hagen, Ed., *The Perception of Pictures*, 1: 137-176, Academic Press: New York, 1980.

[45] Sarkar, M., Snibbe, S. S., Tversky, O. J., Reiss, S. P., "Stretching the rubber sheet: a metaphor for viewing large layouts on small screens", *Proc. of UIST*, 81-91, Nov. 1993.

[46] Schroeder, W., Martin, K., Lorensen, W., *The Visualization Toolkit*, 2nd ed. Prentice Hall PTR: New Jersey, 1998.

[47] Shepard, R.N., Metzler, J., "Mental rotation of three-dimensional objects", *Science*, 171: 701-703, 1971.

[48] Shyi, G.C.W., Huang, S.T.T., "Constructing Three-Dimensional Mental Models From Viewing Two-Dimensional Displays", Chinese Journal of Psychology, 37(2): 101-122, 1995.

[49] Smallman, H., John, M., Oonk, H., Cowen, M., "Information Availability in 2D and 3D Displays", *IEEE Computer Graphics and Applications*, 21(5): 51-57, Sept./Oct. 2001.

[50] Springmeyer, R.R., Blattner, M.M., Max, N.L., "A Characterization of the Scientific Data Analysis Process", *Proc. of IEEE Visualization*, 235 -242, 1992.

[51] St. John, M., Cowen, M.B., Smallman, H.S., Oonk, H.M., "The Use of 2D and 3D Displays for Shape-Understanding Versus Relative-Position Tasks", *Human Factors*, 43(1): 79-98, 2001.

[52] St. John, M., Smallman, H.S., Bank, T.E., Cowen, M.B., "Tactical Routing Using Two-Dimensional and Three-Dimensional Views of Terrain", *Technical Report 1849, SSC San Diego Technical Reports*, January 2001.

[53] Tavanti, M., Lind, M., "2D vs 3D, Implications on Spatial Memory", *Symposium on Information Visualization*, 139-145, 2001.

[54] Thouless, R.H., "Phenomenal Regression to the Real Object", *British Journal of Psychology*, 21: 339-359, 1931.

[55] Tory, M., "Mental Registration of 2D and 3D Visualizations (An Empirical Study)", *Proc. IEEE Visualization 2003*, 371-378, Oct. 2003.

[56] Tory, M., Möller, T., Atkins, M.S., and Kirkpatrick, A.E., "Combining 2D and 3D Views for Orientation and Relative Position Tasks", *Proc. CHI 2004*, April 2004.

[57] Tory, M., Potts, S., and Möller, T., "A Parallel Coordinates Style Interface for Exploratory Volume Visualization", *IEEE Transactions on Visualization and Computer Graphics*, to appear.

[58] Tory, M. and Swindells, C., "Comparing ExoVis, Orientation Icon, and In-Place 3D Visualization Techniques", *Proc. Graphics Interface*, 57-64, June 2003.

[59] Totsuka, T., Levoy, M., "Frequency domain volume rendering", *Computer Graphics*, 27(4): 271-278, August 1993.

[60] Tresens, M.A., "Hybrid-Reality: Collaborative Environment for Biomedical Data Exploration Exploiting 2-D and 3-D Correspondence", *Proc. NSF Lake Tahoe Workshop on Collaborative Virtual Reality and Visualization,* Oct. 2003.

[61] Tufte, E. R., *Envisioning Information*, Graphics Press, 1990.

[62] Van der Heyden, J. E., Carpendale, M. S. T., Inkpen, K. M., Atkins, M. S., "Visual presentation of magnetic resonance images", *Proc. of IEEE Visualization*, 423-426, Oct. 1998.

[63] Van Orden, K.F., Broyles, J.W., "Visuospatial Task Performance as a Function of Two- and Three-Dimensional Display Presentation Techniques", Displays, 21(1): 17-24, March 2000.

[64] Wagemans, J., Van Gool, L., Lamote, C., Foster, D.H., "Minimal Information to Determine Affine Shape Equivalence", Journal of Experimental Psychology: Human Perception & Performance, 26(2): 443-468, Apr. 2000.

[65] Walstein, A., *Cognitive Support in Software Engineering Tools: A Distributed Cognition Framework*, Ph.D. thesis, Simon Fraser University, 2002.

[66] Ware, C., *Information Visualization: Perception for Design*, Morgan Kaufmann Publishers (Academic Press): San Francisco, 2000.

[67] Wehrend, S., Lewis, C., "A Problem-oriented Classification of Visualization Techniques", *Proc. of IEEE Visualization*, 139-143 and 469, 1990.

[68] Westover, L., "Footprint Evaluation for Volume Rendering", *Computer Graphics*, 24(4): 367-376, 1990.

[69] Wickens, C.D., Merwin, D.H., Lin, E.L., "Implications of Graphics Enhancements for the Visualization of Scientific Data: Dimensional integrality, Stereopsis, Motion, and Mesh", Human Factors, 36(1): 44-61, March 1994.

[70] Wong, P.C., Bergeron, D., "Brushing Techniques for Exploring Volume Datasets", *Proc. of IEEE Visualization*, 429 - 432, 1997.

[71] Woods, D.D., "Visual Momentum: a Concept to Improve the Cognitive Coupling of Person and Computer", *International Journal of Man-Machine Studies*, 21: 229-244, 1984.

[72] Zhai, S., Buxton, W., Milgram, P., "The 'Silk Cursor': Investigating Transparency for 3D Target Acquisition," *Proc. of the Conference on Human Factors in Computing Systems* (CHI 1994), 459-464, 1994.

Appendix 1: Definitions and Acronyms

2D View: a slice or orthographic front/back, right/left, or top/bottom projection. A 2D view is a representation of an object or data set that provides information about only two spatial dimensions.

3D View: any representation of an object or data set that directly provides information about 3D spatial structure (depth information). A 3D view is typically a perspective or orthographic projection of an object from a viewing angle other than front/back, right/left, or top/bottom. 3D views include, but are not limited to, stereo projections of objects.

ACM: Association for Computing Machinery.

CAD: Computer Aided Design.

Callout: In ExoVis, a structure that shows details of a 3D subvolume.

Clip Plane: A method for seeing inside objects in computer graphics. When placed in a 3D graphic scene, a clip plane makes all objects in front of it invisible. No mental transformation is needed to register a clip plane and 3D view.

Cutting Plane: A method for seeing inside objects in computer graphics. When placed in a 3D graphic scene, a cutting plane opens up an object (like a book) so it is possible to see inside. No mental transformation is needed to register a cutting plane and 3D view.

df: Degrees of freedom (in statistics).

DOF: Degrees of freedom (for input devices).

ExoVis: A method of providing overview and detail views of 3D data. ExoVis presents a trade-off between orientation icons and in-place detail views such as clip planes and distortion lenses. In ExoVis, the detail view can be translated and scaled from its position in the global view, but cannot be rotated. Hence, mental translation and scaling may be required to register an overview and detail view, but mental rotation is not required.

IEEE: Institute of Electrical and Electronics Engineers.

In-place techniques: A class of detail and context techniques in which the detail views are displayed in their exact locations relative to the overview (i.e. the details are "in-place"). Examples include clip planes, cutting planes, and distortion lenses.

Mental integration: A mental task in which two or more views of a data set or object are combined into a higher order mental structure. For example, five consecutive slices of a medical image volume may be mentally integrated so the person can examine the higher order 3D structure.

Mental registration: (a) A mental transformation in which two or more views of the same data are aligned spatially, and/or (b) knowledge of the transformation required to align two or more views. In other words, understanding how two or more views relate to one another spatially.

Mental rotation: A type of mental transformation in which a mental representation of an object is rotated through intermediate positions in a trajectory, as though the object were being rotated in physical space.

Mental scaling: A type of mental transformation in which a mental representation of an object is scaled through intermediate sizes, as though the object were growing or shrinking in physical space.

Mental translation: A type of mental transformation in which a mental representation of an object is translated through intermediate positions in a trajectory, as though the object were being translated in physical space.

Orientation icon: A view that provides context for other views, but is spatially separated from the other views. (E.g., In a video game, a small map in the corner of the screen with a dot showing the player's position in the virtual world would be an orientation icon.) Overview and detail views may be translated, rotated, and/or scaled relative to one another, so any of these mental transformations may be needed to mentally register the views.

Out-of-place techniques: A class of detail and context techniques in which the details are not displayed in their exact locations relative to the overview (i.e. the details are "out-of-place"). Examples include orientation icons and ExoVis.

Placeholder: An object that indicates the position of an area or volume of interest within a larger context. Used by out-of-place techniques such as orientation icons. For example, in a video game, a dot showing a player's current position on a map icon is a placeholder.

Reference: Same as a placeholder.

ROI: Region of interest. A 2D area of interest.

Slice view: A plane that shows data from a planar cut or cross-section through a data set.

Transfer function: A function that takes a set of input data values and maps them to a set of colours and opacities. Used in direct volume rendering to determine how the data set will appear when rendered.

VOI: Volume of interest. A 3D subvolume.

Wall: In ExoVis, a structure that shows details of a 2D region of interest (typically a slice or 2D orthographic projection).

Appendix 2: Questionnaires

1 Background Questionnaire

This background questionnaire was completed by all participants in both experiments 1 and 2:

How often do you use the following 3D graphics software tools and techniques?

	Never	**Rarely** (few times)	**Occasionally** (at least once per month)	**Often** (at least once per week)	**Very Often** (at least once per day)
3D video games or virtual worlds					
3D visualization /data display tools					
3D modeling software (e.g., AutoCAD, Trispectives, ACIS, 3D StudioMax, etc.)					
3D graphics programming					

What is your gender? Male Female

What is your age? 19-25 26-35 36-45 46-55 56+

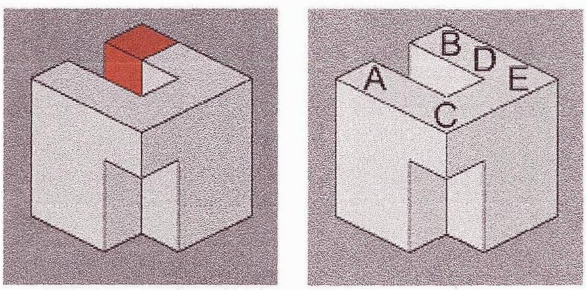
2 Questionnaires for Experiment 1

Orthographic View Experiment

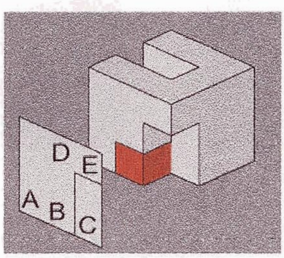
How difficult was the study task with the following types of views?

Very easy — Very difficult

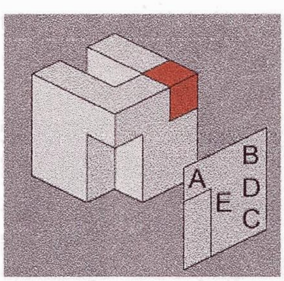
1 2 3 4 5 6 7



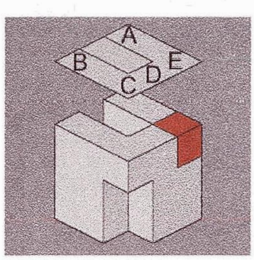
1 2 3 4 5 6 7

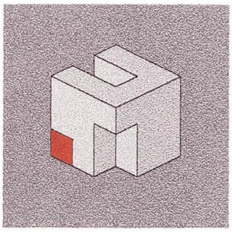


1 2 3 4 5 6 7

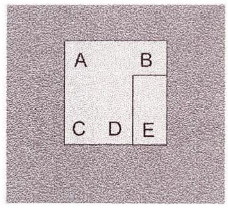


1 2 3 4 5 6 7

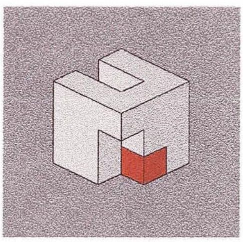




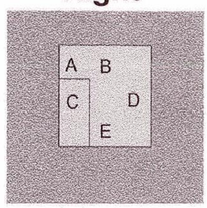
Front



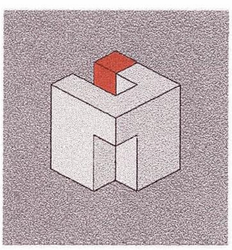
1 2 3 4 5 6 7



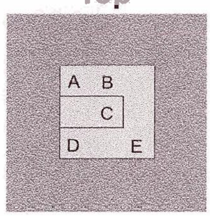
Right



1 2 3 4 5 6 7



Top

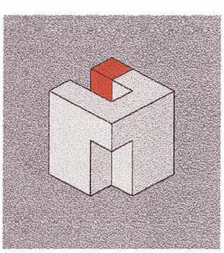


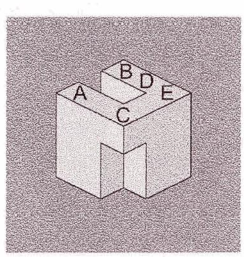
1 2 3 4 5 6 7

Slice View Experiment

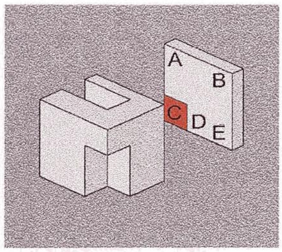
How difficult was the study task with the following types of views?

Very easy Very difficult

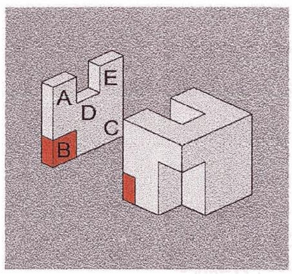




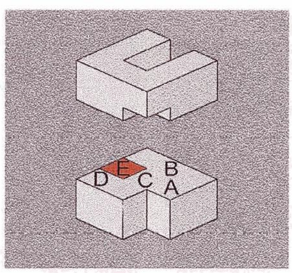
1 2 3 4 5 6 7



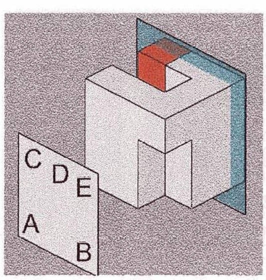
1 2 3 4 5 6 7



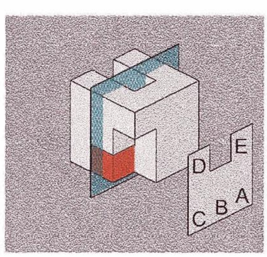
1 2 3 4 5 6 7



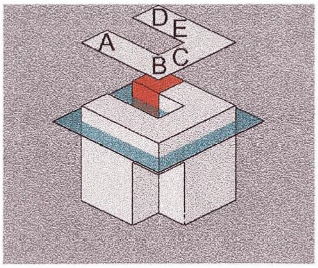
1 2 3 4 5 6 7



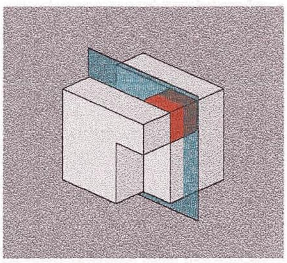
1 2 3 4 5 6 7



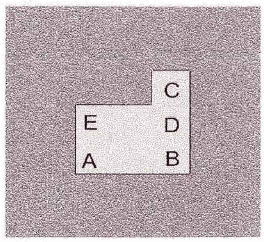
1 2 3 4 5 6 7



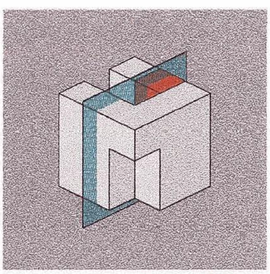
1 2 3 4 5 6 7



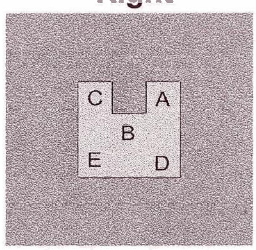
Front



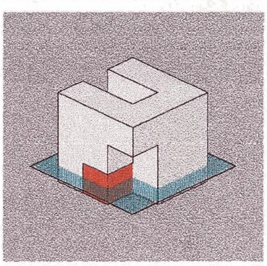
1 2 3 4 5 6 7



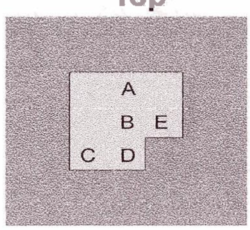
Right



1 2 3 4 5 6 7



Top



1 2 3 4 5 6 7

3 Questionnaires for Experiment 2A

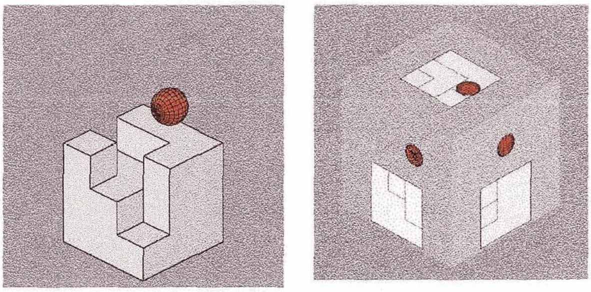
Position Task Questionnaire

How easy was the study task with the following types of views?

Closed Box Display

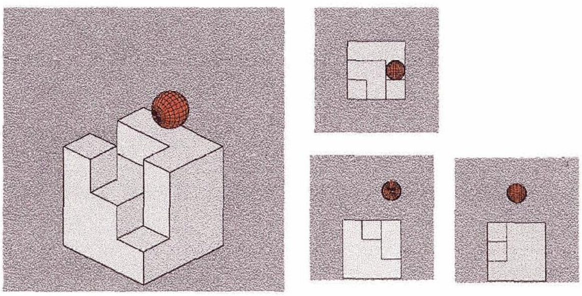
Difficult — Easy

1 2 3 4 5 6 7



Open Box Display

1 2 3 4 5 6 7



Which did you prefer: open-box display closed box display

Why?

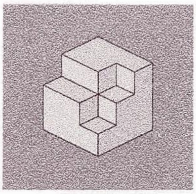
How helpful was the 3D view? Not helpful 1 2 3 4 5 6 7 Very helpful

What was the 3D view useful for?

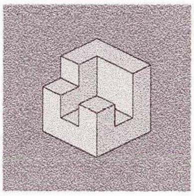
How helpful were the 2D views? Not helpful 1 2 3 4 5 6 7 Very helpful

What were the 2D views useful for?

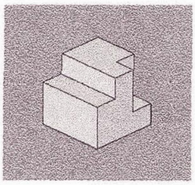
During the experiment, how many times did you see the following shapes?



0 1 2 3 4 5 6



0 1 2 3 4 5 6



0 1 2 3 4 5 6

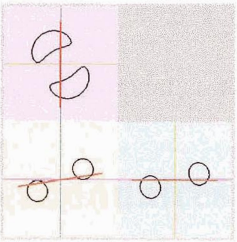
Orientation Task Questionnaire

1. Displays

How easy was the study task with the following types of 2D views?

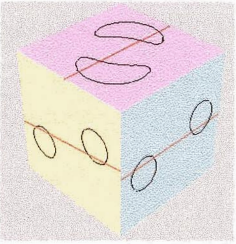
Very difficult Very easy

Separated Display



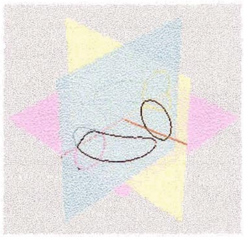
1 2 3 4 5 6 7

Box Display



1 2 3 4 5 6 7

In-place Display



l 2 3 4 5 6 7

Which display did you:	Most prefer:	separated	box	in-place
	Least prefer:	separated	box	in-place

Why?

How helpful was the 3D view? Not helpful 1 2 3 4 5 6 7 Very helpful
What was the 3D view useful for?

How helpful were the 2D views? Not helpful 1 2 3 4 5 6 7 Very helpful
What were the 2D views useful for?

2. Input Device

Using the input device was..

Very difficult	1 2 3 4 5 6 7	Very easy
Boring	1 2 3 4 5 6 7	Fun
Uncomfortable	1 2 3 4 5 6 7	Comfortable
Frustrating	1 2 3 4 5 6 7	Satisfying
Very tiring	1 2 3 4 5 6 7	Not at all tiring

If you have any comments on the input device, you may add them here:

4 Questionnaires for Experiment 2B

Position Task Questionnaire

Rate the study task according to the following criteria:

Overall Difficulty	Very easy	1	2	3	4	5	6	7	Very difficult
Mental Effort	Low effort	1	2	3	4	5	6	7	High effort

Understanding the block's shape	Very easy	1	2	3	4	5	6	7	Very difficult
	Not important for task	1	2	3	4	5	6	7	Very important for task
Understanding which cube the ball was above	Very easy	1	2	3	4	5	6	7	Very difficult
	Not important for task	1	2	3	4	5	6	7	Very important for task
Estimating the ball's height	Very easy	1	2	3	4	5	6	7	Very difficult
	Not important for task	1	2	3	4	5	6	7	Very important for task
Display	Strongly dislike	1	2	3	4	5	6	7	Strongly like

What are the main advantages of the display?
What are the main disadvantages of the display?

What would you change about the display (if anything)?

How helpful were the 3D views? Not helpful 1 2 3 4 5 6 7 Very helpful
What were 3D views useful for?

How helpful were the 2D views? Not helpful 1 2 3 4 5 6 7 Very helpful
What were 2D views useful for?

Orientation Task Questionnaire

Rate the study task according to the following criteria:

Overall Difficulty	Very easy	1	2	3	4	5	6	7	Very difficult
Mental Effort	Low effort	1	2	3	4	5	6	7	High effort
Physical Effort	Low effort	1	2	3	4	5	6	7	High effort

Understanding the **torus's** orientation	Very easy	1	2	3	4	5	6	7	Very difficult
	Not important	1	2	3	4	5	6	7	Very important
Understanding the **plane's** orientation	Very easy	1	2	3	4	5	6	7	Very difficult
	Not important for task	1	2	3	4	5	6	7	Very important
Orienting the plane **approximately**	Very easy	1	2	3	4	5	6	7	Very difficult
	Not important	1	2	3	4	5	6	7	Very important
Orienting the plane **precisely**	Very easy	1	2	3	4	5	6	7	Very difficult
	Not important	1	2	3	4	5	6	7	Very important
Display	Strongly dislike	1	2	3	4	5	6	7	Strongly like

What are the main advantages of the display?
What are the main disadvantages of the display?

What would you change about the display (if anything)?

How helpful was the 3D view? Not helpful 1 2 3 4 5 6 7 Very helpful
What was the 3D view useful for?

How helpful were the 2D slices? Not helpful 1 2 3 4 5 6 7 Very helpful
What were 2D slices useful for?

5 Questionnaires for Experiment 3

Observation Guide

These categories were used to structure the observation and contextual inquiry:

- Confusion about the display, especially how views relate
- Occlusion - Annoyance with and activities to resolve
  (e.g., rotation, turning views on and off, turning placeholders on and off)
- Strategy to complete task
- What each view is used for and when

Interview: Subjective Rating Scale Questions

	Display A (Orientation Icon)	**Display B (ExoVis)**	**Comments**
Display ___ was...	Disagree Agree	Disagree Agree	
• Easy to learn	1 2 3 4 5 6 7	1 2 3 4 5 6 7	
• Clearly organized	1 2 3 4 5 6 7	1 2 3 4 5 6 7	
• Frustrating to use	1 2 3 4 5 6 7	1 2 3 4 5 6 7	
With display ____ it was easy to:			
• Complete the assigned task	1 2 3 4 5 6 7	1 2 3 4 5 6 7	
• Understand how the slices and 3D view related to each other	1 2 3 4 5 6 7	1 2 3 4 5 6 7	
• Move the slices where you wanted	1 2 3 4 5 6 7	1 2 3 4 5 6 7	
• Determine whether the box enclosed the anomaly	1 2 3 4 5 6 7	1 2 3 4 5 6 7	
• Adjust the size of the box	1 2 3 4 5 6 7	1 2 3 4 5 6 7	

Interview: Open-ended Questions

What was the hardest part of this task? Why do you think it was hard?

Which display did you prefer? Why?

What would you change about display A? Display B?

Can you think of a situation where you would prefer to use the other display?

Did you use both the slices and the 3D view? What for?

Appendix 3: Statistical Details

This appendix provides detailed statistical results for experiments 1 and 2. Chapters 7 and 8 described and discussed the statistically significant experimental results, but left out the non-significant results. This appendix provides complete results (as tables from SPSS). P-values for significant results are shaded dark grey, and p-values for marginally significant results are shaded light grey. Note that in some cases 2-tailed test results in this appendix were divided in half, so a one-tailed result was reported in Chapter 7 or 8.

1 Experiment 1A: Orthographic View Experiment

Key: ori = orientation, F = front, R = right, T = top

1.1 Timing Data

Descriptive Statistics

	Mean	Std. Deviation	N
Orientation Icon (front)	1.2617	.28530	12
Orientation Icon (right)	1.2667	.29404	12
Orientation Icon (top)	1.2717	.33978	12
ExoVis (front)	.9417	.22530	12
ExoVis (right)	.9208	.24814	12
ExoVis (top)	.9508	.25557	12

Mauchly's Test of Sphericity[b]

Measure: MEASURE_1

Within Subjects Effect	Mauchly's W	Approx. Chi-Square	df	Sig.	Epsilon[a] Greenhouse-Geisser	Huynh-Feldt	Lower-bound
display	1.000	.000	0	.	1.000	1.000	1.000
ori	.972	.284	2	.868	.973	1.000	.500
display * ori	.919	.842	2	.656	.925	1.000	.500

Tests of Within-Subjects Effects

Measure: MEASURE_1

Source		df	F	Sig.	Partial Eta Squared	Observed Power[a]
display	Sphericity Assumed	1	48.971	.000	.817	1.000
	Greenhouse-Geisser	1.000	48.971	.000	.817	1.000
	Huynh-Feldt	1.000	48.971	.000	.817	1.000
	Lower-bound	1.000	48.971	.000	.817	1.000
Error(display)	Sphericity Assumed	11				
	Greenhouse-Geisser	11.000				
	Huynh-Feldt	11.000				
	Lower-bound	11.000				
ori	Sphericity Assumed	2	.257	.776	.023	.085
	Greenhouse-Geisser	1.946	.257	.770	.023	.085
	Huynh-Feldt	2.000	.257	.776	.023	.085
	Lower-bound	1.000	.257	.622	.023	.075
Error(ori)	Sphericity Assumed	22				
	Greenhouse-Geisser	21.401				
	Huynh-Feldt	22.000				
	Lower-bound	11.000				
display * ori	Sphericity Assumed	2	.249	.782	.022	.084
	Greenhouse-Geisser	1.850	.249	.766	.022	.083
	Huynh-Feldt	2.000	.249	.782	.022	.084
	Lower-bound	1.000	.249	.628	.022	.074
Error(display*ori)	Sphericity Assumed	22				
	Greenhouse-Geisser	20.355				
	Huynh-Feldt	22.000				
	Lower-bound	11.000				

a. Computed using alpha = .05

Pairwise Comparisons

Measure: MEASURE_1

(I) display	(J) display	Mean Difference (I-J)	Std. Error	Sig.[a]	95% Confidence Interval for Difference[a]	
					Lower Bound	Upper Bound
OI	ExoVis	.329*	.047	.000	.225	.432
ExoVis	OI	-.329*	.047	.000	-.432	-.225

Based on estimated marginal means

*. The mean difference is significant at the .05 level.

a. Adjustment for multiple comparisons: Bonferroni.

1.2 Error Data

Test Statistics[a]

N	12
Chi-Square	13.000
df	2
Asymp. Sig.	.002

a. Friedman Test

Test Statistics[c]

	oi_all - Control	exo_all - Control	exo_all - oi_all
Z	-2.588[a]	-1.414[a]	-2.232[b]
Asymp. Sig. (2-tailed)	.010	.157	.026

a. Based on positive ranks.

b. Based on negative ranks.

c. Wilcoxon Signed Ranks Test

1.3 Difficulty Ratings

Test Statistics[a]

N	12
Chi-Square	17.318
df	2
Asymp. Sig.	.000

a. Friedman Test

Test Statistics[c]

	Orientation Icon - Control	ExoVis - Control	ExoVis - Orientation Icon
Z	-2.937[a]	-2.677[a]	-2.443[b]
Asymp. Sig. (2-tailed)	.003	.007	.015

a. Based on negative ranks.

b. Based on positive ranks.

c. Wilcoxon Signed Ranks Test

2 Experiment 1B: Slice View Experiment

2.1 Timing Data

Descriptive Statistics

	Mean	Std. Deviation	N
Orientation Icon (front)	1.3253	.27008	15
Orientation Icon (right)	1.4300	.32922	15
Orientation Icon (top)	1.5600	.30515	15
ExoVis (front)	.9880	.24846	15
ExoVis (right)	.9747	.29174	15
ExoVis (top)	1.0273	.29875	15
In place (front)	.5193	.34437	15
In place (right)	.5540	.37136	15
In place (top)	.5440	.39435	15

Mauchly's Test of Sphericity[b]

Measure: MEASURE_1

Within Subjects Effect	Mauchly's W	Approx. Chi-Square	df	Sig.	Epsilon[a]		
					Greenhouse -Geisser	Huynh -Feldt	Lower-bound
display	.693	4.763	2	.092	.765	.840	.500
ori	.950	.663	2	.718	.953	1.000	.500
display * ori	.368	12.410	9	.195	.727	.937	.250

Tests of Within-Subjects Effects

Measure: MEASURE_1

Source		df	F	Sig.	Partial Eta Squared	Observed Power[a]
display	Sphericity Assumed	2	44.053	.000	.759	1.000
	Greenhouse-Geisser	1.530	44.053	.000	.759	1.000
	Huynh-Feldt	1.681	44.053	.000	.759	1.000
	Lower-bound	1.000	44.053	.000	.759	1.000
Error(display)	Sphericity Assumed	28				
	Greenhouse-Geisser	21.427				
	Huynh-Feldt	23.530				
	Lower-bound	14.000				
ori	Sphericity Assumed	2	11.937	.000	.460	.990
	Greenhouse-Geisser	1.905	11.937	.000	.460	.987
	Huynh-Feldt	2.000	11.937	.000	.460	.990
	Lower-bound	1.000	11.937	.004	.460	.894
Error(ori)	Sphericity Assumed	28				
	Greenhouse-Geisser	26.675				
	Huynh-Feldt	28.000				
	Lower-bound	14.000				
display * ori	Sphericity Assumed	4	6.075	.000	.303	.979
	Greenhouse-Geisser	2.907	6.075	.002	.303	.937
	Huynh-Feldt	3.750	6.075	.001	.303	.973
	Lower-bound	1.000	6.075	.027	.303	.631
Error(display*ori)	Sphericity Assumed	56				
	Greenhouse-Geisser	40.692				
	Huynh-Feldt	52.498				
	Lower-bound	14.000				

a. Computed using alpha = .05

Pairwise Comparisons

Measure: MEASURE_1

(I) display	(J) display	Mean Difference (I-J)	Std. Error	Sig.[a]	95% Confidence Interval for Difference[a]	
					Lower Bound	Upper Bound
OI	ExoVis	.442*	.070	.000	.251	.633
	IP	.899*	.117	.000	.581	1.218
ExoVis	OI	-.442*	.070	.000	-.633	-.251
	IP	.458*	.094	.001	.202	.714
IP	OI	-.899*	.117	.000	-1.218	-.581
	ExoVis	-.458*	.094	.001	-.714	-.202

Based on estimated marginal means

*. The mean difference is significant at the .05 level.

a. Adjustment for multiple comparisons: Bonferroni.

Pairwise Comparisons

Measure: MEASURE_1

(I) ori	(J) ori	Mean Difference (I-J)	Std. Error	Sig.[a]	95% Confidence Interval for Difference[a]	
					Lower Bound	Upper Bound
F	R	-.042	.018	.106	-.091	.007
	T	-.100*	.021	.001	-.158	-.042
R	F	.042	.018	.106	-.007	.091
	T	-.058	.022	.058	-.117	.002
T	F	.100*	.021	.001	.042	.158
	R	.058	.022	.058	-.002	.117

Based on estimated marginal means

*. The mean difference is significant at the .05 level.

a. Adjustment for multiple comparisons: Bonferroni.

Pairwise Comparisons

Measure: MEASURE_1

ori	(I) display	(J) display	Mean Difference (I-J)	Std. Error	Sig.[a]	95% Confidence Interval for Difference[a]	
						Lower Bound	Upper Bound
F	OI	ExoVis	.337*	.062	.000	.170	.505
		IP	.806*	.113	.000	.499	1.113
	ExoVis	OI	-.337*	.062	.000	-.505	-.170
		IP	.469*	.096	.001	.207	.730
	IP	OI	-.806*	.113	.000	-1.113	-.499
		ExoVis	-.469*	.096	.001	-.730	-.207
R	OI	ExoVis	.455*	.093	.001	.202	.709
		IP	.876*	.123	.000	.543	1.209
	ExoVis	OI	-.455*	.093	.001	-.709	-.202
		IP	.421*	.091	.001	.173	.669
	IP	OI	-.876*	.123	.000	-1.209	-.543
		ExoVis	-.421*	.091	.001	-.669	-.173
T	OI	ExoVis	.533*	.073	.000	.334	.731
		IP	1.016*	.128	.000	.669	1.363
	ExoVis	OI	-.533*	.073	.000	-.731	-.334
		IP	.483*	.102	.001	.207	.760
	IP	OI	-1.016*	.128	.000	-1.363	-.669
		ExoVis	-.483*	.102	.001	-.760	-.207

Based on estimated marginal means

*. The mean difference is significant at the .05 level.

a. Adjustment for multiple comparisons: Bonferroni.

Pairwise Comparisons

Measure: MEASURE_1

display	(I) ori	(J) ori	Mean Difference (I-J)	Std. Error	Sig.[a]	95% Confidence Interval for Difference[a] Lower Bound	Upper Bound
OI	F	R	-.105	.047	.130	-.233	.023
		T	-.235*	.049	.001	-.368	-.101
	R	F	.105	.047	.130	-.023	.233
		T	-.130	.052	.080	-.273	.013
	T	F	.235*	.049	.001	.101	.368
		R	.130	.052	.080	-.013	.273
ExoVis	F	R	.013	.028	1.000	-.063	.090
		T	-.039	.030	.651	-.122	.043
	R	F	-.013	.028	1.000	-.090	.063
		T	-.053	.026	.178	-.122	.017
	T	F	.039	.030	.651	-.043	.122
		R	.053	.026	.178	-.017	.122
IP	F	R	-.035	.018	.219	-.083	.014
		T	-.025	.025	1.000	-.093	.044
	R	F	.035	.018	.219	-.014	.083
		T	.010	.019	1.000	-.041	.061
	T	F	.025	.025	1.000	-.044	.093
		R	-.010	.019	1.000	-.061	.041

Based on estimated marginal means

*. The mean difference is significant at the .05 level.

a. Adjustment for multiple comparisons: Bonferroni.

2.2 Error Data

Test Statistics[a]

N	15
Chi-Square	25.737
df	3
Asymp. Sig.	.000

a. Friedman Test

Test Statistics[b]

	ExoVis - Orientation Icon	In place - Orientation Icon	In place - ExoVis
Z	-2.716[a]	-2.714[a]	-1.000[a]
Asymp. Sig. (2-tailed)	.007	.007	.317

a. Based on negative ranks.

b. Wilcoxon Signed Ranks Test

2.3 Difficulty Ratings

Test Statistics[a]

N	15
Chi-Square	26.043
df	3
Asymp. Sig.	.000

a. Friedman Test

Test Statistics[c]

	Orientation Icon - Control	ExoVis - Control	In place - Control	ExoVis - Orientation Icon	In place - Orientation Icon	In place - ExoVis
Z	-3.410[a]	-1.654[a]	-.211[b]	-3.418[b]	-3.112[b]	-1.296[b]
Asymp. Sig. (2-tailed)	.001	.098	.833	.001	.002	.195

a. Based on negative ranks.

b. Based on positive ranks.

c. Wilcoxon Signed Ranks Test

3 Experiment 2A: Combining Multiple 2D Views

3.1 Relative Position Task

Key: DISFIRST = display participants saw first, SEP = separated display, BOX = box display, start_sep = separated display first, start_box = box display first. Numbers 1-3 represent ball heights (Note: subtract 1 from these ball heights when comparing this data with results in chapter 8).

3.1.1 Timing Data

Descriptive Statistics

	DISFIRST	Mean	Std. Deviation	N
SEP_1	start_sep	2.0594	.74052	6
	start_box	1.7898	.46805	5
	Total	1.9368	.61776	11
SEP_2	start_sep	2.3079	.64344	6
	start_box	1.8619	.46135	5
	Total	2.1052	.58855	11
SEP_3	start_sep	2.5034	.69810	6
	start_box	2.1769	.56575	5
	Total	2.3550	.63307	11
BOX_1	start_sep	1.9400	.64770	6
	start_box	1.7420	.41937	5
	Total	1.8500	.53926	11
BOX_2	start_sep	1.9883	.50547	6
	start_box	2.1340	.49868	5
	Total	2.0545	.48271	11
BOX_3	start_sep	2.1467	.52435	6
	start_box	2.2560	.51685	5
	Total	2.1964	.49758	11

Mauchly's Test of Sphericity[b]

Measure: MEASURE_1

					Epsilon[a]		
Within Subjects Effect	Mauchly's W	Approx. Chi-Square	df	Sig.	Greenhouse-Geisser	Huynh-Feldt	Lower-bound
DISPLAY	1.000	.000	0	.	1.000	1.000	1.000
HEIGHT	.678	3.109	2	.211	.756	.978	.500
DISPLAY * HEIGHT	.794	1.846	2	.397	.829	1.000	.500

Tests of Within-Subjects Effects

Measure: MEASURE_1

Source		df	F	Sig.	Partial Eta Squared	Observed Power[a]
DISPLAY	Sphericity Assumed	1	1.318	.281	.128	.177
	Greenhouse-Geisser	1.000	1.318	.281	.128	.177
	Huynh-Feldt	1.000	1.318	.281	.128	.177
	Lower-bound	1.000	1.318	.281	.128	.177
DISPLAY * DISFIRST	Sphericity Assumed	1	6.568	.031	.422	.627
	Greenhouse-Geisser	1.000	6.568	.031	.422	.627
	Huynh-Feldt	1.000	6.568	.031	.422	.627
	Lower-bound	1.000	6.568	.031	.422	.627
Error(DISPLAY)	Sphericity Assumed	9				
	Greenhouse-Geisser	9.000				
	Huynh-Feldt	9.000				
	Lower-bound	9.000				
HEIGHT	Sphericity Assumed	2	43.535	.000	.829	1.000
	Greenhouse-Geisser	1.513	43.535	.000	.829	1.000
	Huynh-Feldt	1.956	43.535	.000	.829	1.000
	Lower-bound	1.000	43.535	.000	.829	1.000
HEIGHT * DISFIRST	Sphericity Assumed	2	1.175	.331	.115	.225
	Greenhouse-Geisser	1.513	1.175	.323	.115	.196
	Huynh-Feldt	1.956	1.175	.331	.115	.222
	Lower-bound	1.000	1.175	.307	.115	.163
Error(HEIGHT)	Sphericity Assumed	18				
	Greenhouse-Geisser	13.62				
	Huynh-Feldt	17.60				
	Lower-bound	9.000				
DISPLAY * HEIGHT	Sphericity Assumed	2	1.695	.212	.158	.309
	Greenhouse-Geisser	1.658	1.695	.218	.158	.278
	Huynh-Feldt	2.000	1.695	.212	.158	.309
	Lower-bound	1.000	1.695	.225	.158	.214
DISPLAY * HEIGHT * DISFIRST	Sphericity Assumed	2	9.113	.002	.503	.948
	Greenhouse-Geisser	1.658	9.113	.004	.503	.912
	Huynh-Feldt	2.000	9.113	.002	.503	.948
	Lower-bound	1.000	9.113	.015	.503	.766
Error(DISPLAY*HEIGHT)	Sphericity Assumed	18				
	Greenhouse-Geisser	14.92				
	Huynh-Feldt	18.00				
	Lower-bound	9.000				

a. Computed using alpha = .05

Pairwise Comparisons

Measure: MEASURE_1

(I) HEIGHT	(J) HEIGHT	Mean Difference (I-J)	Std. Error	Sig.[a]	95% Confidence Interval for Difference[a]	
					Lower Bound	Upper Bound
1	2	-.190*	.043	.005	-.316	-6.411E-02
	3	-.388*	.050	.000	-.535	-.241
2	1	.190*	.043	.005	6.411E-02	.316
	3	-.198*	.029	.000	-.282	-.113
3	1	.388*	.050	.000	.241	.535
	2	.198*	.029	.000	.113	.282

Based on estimated marginal means

*. The mean difference is significant at the .05 level.

a. Adjustment for multiple comparisons: Bonferroni.

Pairwise Comparisons

Measure: MEASURE_1

DISPLAY	(I) DISFIRST	(J) DISFIRST	Mean Difference (I-J)	Std. Error	Sig.[a]	95% Confidence Interval for Difference[a]	
						Lower Bound	Upper Bound
SEP	start_sep	start_box	.347	.367	.369	-.484	1.178
	start_box	start_sep	-.347	.367	.369	-1.178	.484
BOX	start_sep	start_box	-.019	.315	.953	-.731	.693
	start_box	start_sep	1.900E-02	.315	.953	-.693	.731

Based on estimated marginal means

a. Adjustment for multiple comparisons: Bonferroni.

Measure: MEASURE_1

DISFIRST	(I) DISPLAY	(J) DISPLAY	Mean Difference (I-J)	Std. Error	Sig.[a]	95% Confidence Interval for Difference[a]	
						Lower Bound	Upper Bound
start_sep	SEP	BOX	.265*	.096	.022	4.720E-02	.483
	BOX	SEP	-.265*	.096	.022	-.483	-4.720E-02
start_box	SEP	BOX	-.101	.106	.363	-.340	.138
	BOX	SEP	.101	.106	.363	-.138	.340

Based on estimated marginal means

*. The mean difference is significant at the .05 level.

a. Adjustment for multiple comparisons: Bonferroni.

3.1.2 Difficulty Ratings

Test Statistics[b]

	box - sep
Z	-2.309[a]
Asymp. Sig. (2-tailed)	.021

a. Based on negative ranks.

b. Wilcoxon Signed Ranks Test

3.2 Orientation Task

Key: SEP = separated display, BOX = box display, IP = in-place display.

3.2.1 Timing Data

Descriptive Statistics

	Mean	Std. Deviation	N
SEP	3.0100	.45154	12
BOX	2.9653	.57393	12
IP	2.9475	.45661	12

Mauchly's Test of Sphericity[b]

Measure: MEASURE_1

					Epsilon[a]		
Within Subjects Effect	Mauchly's W	Approx. Chi-Square	df	Sig.	Greenhouse -Geisser	Huynh -Feldt	Lower-bound
DISPLAY	.946	.554	2	.758	.949	1.000	.500

Tests of Within-Subjects Effects

Measure: MEASURE_1

Source		df	F	Sig.	Partial Eta Squared	Observed Power[a]
DISPLAY	Sphericity Assumed	2	.150	.861	.013	.070
	Greenhouse-Geisser	1.898	.150	.851	.013	.070
	Huynh-Feldt	2.000	.150	.861	.013	.070
	Lower-bound	1.000	.150	.706	.013	.065
Error(DISPLAY)	Sphericity Assumed	22				
	Greenhouse-Geisser	20.87				
	Huynh-Feldt	22.00				
	Lower-bound	11.00				

a. Computed using alpha = .05

3.2.2 Error Data

Descriptive Statistics

	Mean	Std. Deviation	N
SEP	.7685	.77198	7
BOX	.6239	.64467	7
IP	.6837	.47117	7

Mauchly's Test of Sphericity[b]

Measure: MEASURE_1

Within Subjects Effect	Mauchly's W	Approx. Chi-Square	df	Sig.	Epsilon[a]		
					Greenhouse-Geisser	Huynh-Feldt	Lower-bound
DISPLAY	.817	1.214	2	.545	.845	1.000	.500

Tests of Within-Subjects Effects

Measure: MEASURE_1

Source		df	F	Sig.	Partial Eta Squared	Observed Power[a]
DISPLAY	Sphericity Assumed	2	.408	.673	.055	.103
	Greenhouse-Geisser	1.690	.408	.641	.055	.098
	Huynh-Feldt	2.000	.408	.673	.055	.103
	Lower-bound	1.000	.408	.543	.055	.086
Error(DISPLAY)	Sphericity Assumed	14				
	Greenhouse-Geisser	11.833				
	Huynh-Feldt	14.000				
	Lower-bound	7.000				

a. Computed using alpha = .05

3.2.3 Difficulty Ratings

Test Statistics[a]

N	12
Chi-Square	10.609
df	2
Asymp. Sig.	.005

a. Friedman Test

Test Statistics[c]

	box - sep	ip - sep	ip - box
Z	-.418[a]	-2.852[b]	-2.789[b]
Asymp. Sig. (2-tailed)	.676	.004	.005

a. Based on negative ranks.

b. Based on positive ranks.

c. Wilcoxon Signed Ranks Test

4 Experiment 2B: Combining 2D and 3D Views

4.1 Relative Position Task

Key: 2D = 2D display, 3D R = 3D rotated display, OI = orientation icon, 3D S = 3D shadow display, numbers (0.0 - 2.0) represent ball heights.

4.1.1 Timing Data

Descriptive Statistics

	DISPLAY	Mean	Std. Deviation	N
0.0	2D	2.4959	.68738	8
	3D R	2.5662	.60965	8
	ExoVis	2.2500	.40433	8
	OI	2.5598	.45692	8
	3D S	.9724	.37761	8
	Total	2.1688	.79032	40
0.5	2D	2.6854	.53677	8
	3D R	3.1040	.79611	8
	ExoVis	2.4215	.44072	8
	OI	2.6178	.38901	8
	3D S	1.5045	.42202	8
	Total	2.4667	.74001	40
1.0	2D	2.9583	.56202	8
	3D R	3.1246	.56919	8
	ExoVis	2.7585	.57963	8
	OI	2.7736	.56308	8
	3D S	1.9841	.59099	8
	Total	2.7198	.67227	40
1.5	2D	2.9639	.52700	8
	3D R	2.9125	.82845	8
	ExoVis	2.6834	.56267	8
	OI	2.8498	.50648	8
	3D S	1.9806	.39774	8
	Total	2.6780	.66193	40
2.0	2D	2.8432	.53355	8
	3D R	3.0731	.57481	8
	ExoVis	2.5592	.59936	8
	OI	2.8125	.53708	8
	3D S	2.2442	.38826	8
	Total	2.7064	.57939	40

Mauchly's Test of Sphericity[b]

Measure: MEASURE_1

					Epsilon[a]		
Within Subjects Effect	Mauchly's W	Approx. Chi-Square	df	Sig.	Greenhouse -Geisser	Huynh-Feldt	Lower-bound
HEIGHT	.669	13.430	9	.145	.853	1.000	.250

Tests of Within-Subjects Effects

Measure: MEASURE_1

Source		df	F	Sig.	Partial Eta Squared	Observed Power[a]
HEIGHT	Sphericity Assumed	4	21.91	.000	.385	1.000
	Greenhouse-Geisser	3.41	21.91	.000	.385	1.000
	Huynh-Feldt	4.00	21.91	.000	.385	1.000
	Lower-bound	1.00	21.91	.000	.385	.995
HEIGHT * DISPLAY	Sphericity Assumed	16	2.540	.002	.225	.990
	Greenhouse-Geisser	13.7	2.540	.003	.225	.978
	Huynh-Feldt	16.0	2.540	.002	.225	.990
	Lower-bound	4.00	2.540	.057	.225	.657
Error(HEIGHT)	Sphericity Assumed	140				
	Greenhouse-Geisser	119				
	Huynh-Feldt	140				
	Lower-bound	35.0				

a. Computed using alpha = .05

Tests of Between-Subjects Effects

Measure: MEASURE_1

Transformed Variable: Average

Source	df	F	Sig.	Partial Eta Squared	Observed Power[a]
Intercept	1	1174	.000	.971	1.000
DISPLAY	4	8.255	.000	.485	.996
Error	35				

a. Computed using alpha = .05

Multiple Comparisons

Measure: MEASURE_1
Tukey HSD

(I) DISPLAY	(J) DISPLAY	Mean Difference (I-J)	Std. Error	Sig.	95% Confidence Interval	
					Lower Bound	Upper Bound
2D	3D R	-.1667	.2352	.953	-.8428	.5093
	ExoVis	.2548	.2352	.814	-.4212	.9309
	OI	.0666	.2352	.999	-.6094	.7427
	3D S	1.0522*	.2352	.001	.3761	1.7282
3D R	2D	.1667	.2352	.953	-.5093	.8428
	ExoVis	.4216	.2352	.394	-.2545	1.0976
	OI	.2334	.2352	.857	-.4427	.9095
	3D S	1.2189*	.2352	.000	.5428	1.8950
ExoVis	2D	-.2548	.2352	.814	-.9309	.4212
	3D R	-.4216	.2352	.394	-1.0976	.2545
	OI	-.1882	.2352	.929	-.8643	.4879
	3D S	.7973*	.2352	.014	.1213	1.4734
OI	2D	-.0666	.2352	.999	-.7427	.6094
	3D R	-.2334	.2352	.857	-.9095	.4427
	ExoVis	.1882	.2352	.929	-.4879	.8643
	3D S	.9855*	.2352	.002	.3095	1.6616
3D S	2D	-1.0522*	.2352	.001	-1.7282	-.3761
	3D R	-1.2189*	.2352	.000	-1.8950	-.5428
	ExoVis	-.7973*	.2352	.014	-1.4734	-.1213
	OI	-.9855*	.2352	.002	-1.6616	-.3095

Based on observed means.

*. The mean difference is significant at the .05 level.

Pairwise Comparisons

Measure: MEASURE_1

(I) HEIGHT	(J) HEIGHT	Mean Difference (I-J)	Std. Error	Sig.[a]	95% Confidence Interval for Difference[a]	
					Lower Bound	Upper Bound
.0	.5	-.298*	.072	.002	-.513	-.083
	1.0	-.551*	.067	.000	-.752	-.350
	1.5	-.509*	.084	.000	-.762	-.256
	2.0	-.538*	.073	.000	-.755	-.320
.5	0	.298*	.072	.002	.083	.513
	1.0	-.253*	.049	.000	-.400	-.106
	1.5	-.211	.079	.109	-.447	.024
	2.0	-.240*	.066	.009	-.438	-.042
1.0	0	.551*	.067	.000	.350	.752
	.5	.253*	.049	.000	.106	.400
	1.5	.042	.078	1.00	-.191	.274
	2.0	.013	.070	1.00	-.198	.224
1.5	0	.509*	.084	.000	.256	.762
	.5	.211	.079	.109	-.024	.447
	1.0	-.042	.078	1.00	-.274	.191
	2.0	-.028	.069	1.00	-.234	.177
2.0	0	.538*	.073	.000	.320	.755
	.5	.240*	.066	.009	.042	.438
	1.0	-.013	.070	1.00	-.224	.198
	1.5	.028	.069	1.00	-.177	.234

Based on estimated marginal means

*. The mean difference is significant at the .05 level.

a. Adjustment for multiple comparisons: Bonferroni.

Pairwise Comparisons

Measure: MEASURE_1

HEIGHT	(I) DISPLAY	(J) DISPLAY	Mean Difference (I-J)	Std. Error	Sig.[a]	95% Confidence Interval for Difference[a]	
						Lower Bound	Upper Bound
.0	2D	3D R	-.070	.261	1.00	-.851	.711
		ExoVis	.246	.261	1.00	-.535	1.027
		OI	-.064	.261	1.00	-.845	.717
		3D S	1.524*	.261	.000	.743	2.305
	3D R	2D	.070	.261	1.00	-.711	.851
		ExoVis	.316	.261	1.00	-.465	1.097
		OI	.006	.261	1.00	-.775	.787
		3D S	1.594*	.261	.000	.813	2.375
	ExoVis	2D	-.246	.261	1.00	-1.027	.535
		3D R	-.316	.261	1.00	-1.097	.465
		OI	-.310	.261	1.00	-1.091	.471
		3D S	1.278*	.261	.000	.497	2.059
	OI	2D	.064	.261	1.00	-.717	.845
		3D R	-.006	.261	1.00	-.787	.775
		ExoVis	.310	.261	1.00	-.471	1.091
		3D S	1.587*	.261	.000	.806	2.368
	3D S	2D	-1.524*	.261	.000	-2.305	-.743
		3D R	-1.594*	.261	.000	-2.375	-.813
		ExoVis	-1.278*	.261	.000	-2.059	-.497
		OI	-1.587*	.261	.000	-2.368	-.806
.5	2D	3D R	-.419	.269	1.00	-1.224	.387
		ExoVis	.264	.269	1.00	-.541	1.069
		OI	.068	.269	1.00	-.738	.873
		3D S	1.181*	.269	.001	.375	1.986
	3D R	2D	.419	.269	1.00	-.387	1.224
		ExoVis	.683	.269	.157	-.123	1.488
		OI	.486	.269	.791	-.319	1.292
		3D S	1.600*	.269	.000	.794	2.405
	ExoVis	2D	-.264	.269	1.00	-1.069	.541
		3D R	-.683	.269	.157	-1.488	.123
		OI	-.196	.269	1.00	-1.002	.609
		3D S	.917*	.269	.016	.111	1.722
	OI	2D	-.068	.269	1.00	-.873	.738
		3D R	-.486	.269	.791	-1.292	.319
		ExoVis	.196	.269	1.00	-.609	1.002
		3D S	1.113*	.269	.002	.308	1.919
	3D S	2D	-1.181*	.269	.001	-1.986	-.375
		3D R	-1.600*	.269	.000	-2.405	-.794
		ExoVis	-.917*	.269	.016	-1.722	-.111
		OI	-1.113*	.269	.002	-1.919	-.308
1.0	2D	3D R	-.166	.287	1.00	-1.025	.692
		ExoVis	.200	.287	1.00	-.659	1.058
		OI	.185	.287	1.00	-.674	1.043
		3D S	.974*	.287	.017	.116	1.833
	3D R	2D	.166	.287	1.00	-.692	1.025
		ExoVis	.366	.287	1.00	-.492	1.225
		OI	.351	.287	1.00	-.508	1.209
		3D S	1.140*	.287	.003	.282	1.999
	ExoVis	2D	-.200	.287	1.00	-1.058	.659
		3D R	-.366	.287	1.00	-1.225	.492
		OI	-.015	.287	1.00	-.874	.843
		3D S	.774	.287	.105	-.084	1.633

	OI	2D	-.185	.287	1.00	-1.043	.674
		3D R	-.351	.287	1.00	-1.209	.508
		ExoVis	.015	.287	1.00	-.843	.874
		3D S	.790	.287	.092	-.069	1.648
	3D S	2D	-.974*	.287	.017	-1.833	-.116
		3D R	-1.140*	.287	.003	-1.999	-.282
		ExoVis	-.774	.287	.105	-1.633	.084
		OI	-.790	.287	.092	-1.648	.069
1.5	2D	3D R	.051	.291	1.00	-.821	.924
		ExoVis	.280	.291	1.00	-.592	1.153
		OI	.114	.291	1.00	-.758	.986
		3D S	.983*	.291	.018	.111	1.856
	3D R	2D	-.051	.291	1.00	-.924	.821
		ExoVis	.229	.291	1.00	-.643	1.101
		OI	.063	.291	1.00	-.810	.935
		3D S	.932*	.291	.029	.060	1.804
	ExoVis	2D	-.280	.291	1.00	-1.153	.592
		3D R	-.229	.291	1.00	-1.101	.643
		OI	-.166	.291	1.00	-1.039	.706
		3D S	.703	.291	.212	-.170	1.575
	OI	2D	-.114	.291	1.00	-.986	.758
		3D R	-.063	.291	1.00	-.935	.810
		ExoVis	.166	.291	1.00	-.706	1.039
		3D S	.869	.291	.051	-.003	1.741
	3D S	2D	-.983*	.291	.018	-1.856	-.111
		3D R	-.932*	.291	.029	-1.804	-.060
		ExoVis	-.703	.291	.212	-1.575	.170
		OI	-.869	.291	.051	-1.741	.003
2.0	2D	3D R	-.230	.266	1.00	-1.026	.567
		ExoVis	.284	.266	1.00	-.512	1.081
		OI	.031	.266	1.00	-.766	.827
		3D S	.599	.266	.306	-.198	1.395
	3D R	2D	.230	.266	1.00	-.567	1.026
		ExoVis	.514	.266	.614	-.283	1.310
		OI	.261	.266	1.00	-.536	1.057
		3D S	.829*	.266	.036	.032	1.625
	ExoVis	2D	-.284	.266	1.00	-1.081	.512
		3D R	-.514	.266	.614	-1.310	.283
		OI	-.253	.266	1.00	-1.050	.543
		3D S	.315	.266	1.00	-.482	1.111
	OI	2D	-.031	.266	1.00	-.827	.766
		3D R	-.261	.266	1.00	-1.057	.536
		ExoVis	.253	.266	1.00	-.543	1.050
		3D S	.568	.266	.396	-.228	1.365
	3D S	2D	-.599	.266	.306	-1.395	.198
		3D R	-.829*	.266	.036	-1.625	-.032
		ExoVis	**-.315**	**.266**	**1.00**	**-1.111**	**.482**
		OI	-.568	.266	.396	-1.365	.228

Based on estimated marginal means

*. The mean difference is significant at the .05 level.

a. Adjustment for multiple comparisons: Bonferroni.

Pairwise Comparisons

Measure: MEASURE_1

DISPLAY	(I) HEIGHT	(J) HEIGHT	Mean Difference (I-J)	Std. Error	Sig. [a]	95% Confidence Interval for Difference [a] Lower Bound	Upper Bound
2D	.0	.5	-.190	.160	1.0	-.670	.291
		1.0	-.462*	.150	.039	-.911	-.014
		1.5	-.468	.189	.182	-1.034	.098
		2.0	-.347	.163	.397	-.834	.140
	.5	0	.190	.160	1.0	-.291	.670
		1.0	-.273	.109	.176	-.601	.055
		1.5	-.278	.176	1.0	-.805	.248
		2.0	-.158	.148	1.0	-.601	.285
	1.5	0	.462*	.150	.039	.014	.911
		.5	.273	.109	.176	-.055	.601
		1.5	-.006	.174	1.0	-.525	.514
		2.0	.115	.157	1.0	-.356	.587
	1.5	0	.468	.189	.182	-.098	1.034
		.5	.278	.176	1.0	-.248	.805
		1.0	.006	.174	1.0	-.514	.525
		2.0	.121	.153	1.0	-.338	.580
	2.0	0	.347	.163	.397	-.140	.834
		.5	.158	.148	1.0	-.285	.601
		1.0	-.115	.157	1.0	-.587	.356
		1.5	-.121	.153	1.0	-.580	.338
3D R	.0	.5	-.538*	.160	.019	-1.018	-.057
		1.0	-.558*	.150	.007	-1.007	-.110
		1.5	-.346	.189	.752	-.912	.219
		2.0	-.507*	.163	.036	-.994	-.020
	.5	0	.538*	.160	.019	.057	1.018
		1.0	-.021	.109	1.0	-.349	.307
		1.5	.192	.176	1.0	-.335	.718
		2.0	.031	.148	1.0	-.412	.474
	1.5	0	.558*	.150	.007	.110	1.007
		.5	.021	.109	1.0	-.307	.349
		1.5	.212	.174	1.0	-.308	.732
		2.0	.052	.157	1.0	-.420	.523
	1.5	0	.346	.189	.752	-.219	.912
		.5	-.192	.176	1.0	-.718	.335
		1.0	-.212	.174	1.0	-.732	.308
		2.0	-.161	.153	1.0	-.620	.298
	2.0	0	.507*	.163	.036	.020	.994
		.5	-.031	.148	1.0	-.474	.412
		1.0	-.052	.157	1.0	-.523	.420
		1.5	.161	.153	1.0	-.298	.620
ExoVis	.0	.5	-.172	.160	1.0	-.652	.309
		1.0	-.509*	.150	.017	-.957	-.060
		1.5	-.433	.189	.278	-.999	.132
		2.0	-.309	.163	.654	-.796	.178
	.5	0	.172	.160	1.0	-.309	.652
		1.0	-.337*	.109	.040	-.665	-.009
		1.5	-.262	.176	1.0	-.788	.264
		2.0	-.138	.148	1.0	-.581	.305
	1.5	0	.509*	.150	.017	.060	.957
		.5	.337*	.109	.040	.009	.665
		1.5	.075	.174	1.0	-.445	.595
		2.0	.199	.157	1.0	-.272	.671

	1.5	0	.433	.189	.278	-.132	.999
		.5	.262	.176	1.0	-.264	.788
		1.0	-.075	.174	1.0	-.595	.445
		2.0	.124	.153	1.0	-.335	.583
	2.0	0	.309	.163	.654	-.178	.796
		.5	.138	.148	1.0	-.305	.581
		1.0	-.199	.157	1.0	-.671	.272
		1.5	-.124	.153	1.0	-.583	.335
OI	.0	.5	-.058	.160	1.0	-.539	.423
		1.0	-.214	.150	1.0	-.662	.235
		1.5	-.290	.189	1.0	-.856	.276
		2.0	-.253	.163	1.0	-.740	.234
	.5	0	.058	.160	1.0	-.423	.539
		1.0	-.156	.109	1.0	-.484	.172
		1.5	-.232	.176	1.0	-.758	.294
		2.0	-.195	.148	1.0	-.638	.248
	1.5	0	.214	.150	1.0	-.235	.662
		.5	.156	.109	1.0	-.172	.484
		1.5	-.076	.174	1.0	-.596	.444
		2.0	-.039	.157	1.0	-.510	.433
	1.5	0	.290	.189	1.0	-.276	.856
		.5	.232	.176	1.0	-.294	.758
		1.0	.076	.174	1.0	-.444	.596
		2.0	.037	.153	1.0	-.422	.496
	2.0	0	.253	.163	1.0	-.234	.740
		.5	.195	.148	1.0	-.248	.638
		1.0	.039	.157	1.0	-.433	.510
		1.5	-.037	.153	1.0	-.496	.422
3D S	.0	.5	-.532*	.160	.021	-1.013	-.052
		1.0	-1.012*	.150	.000	-1.460	-.563
		1.5	-1.008*	.189	.000	-1.574	-.443
		2.0	-1.272*	.163	.000	-1.759	-.785
	.5	0	.532*	.160	.021	.052	1.013
		1.0	-.480*	.109	.001	-.808	-.152
		1.5	-.476	.176	.103	-1.002	.050
		2.0	-.740*	.148	.000	-1.183	-.297
	1.5	0	1.012*	.150	.000	.563	1.460
		.5	.480*	.109	.001	.152	.808
		1.5	.003	.174	1.0	-.516	.523
		2.0	-.260	.157	1.0	-.732	.211
	1.5	0	1.008*	.189	.000	.443	1.574
		.5	.476	.176	.103	-.050	1.002
		1.0	-.003	.174	1.0	-.523	.516
		2.0	-.264	.153	.941	-.723	.195
	2.0	0	1.272*	.163	.000	.785	1.759
		.5	.740*	.148	.000	.297	1.183
		1.0	**.260**	**.157**	**1.0**	**-.211**	**.732**
		1.5	.264	.153	.941	-.195	.723

Based on estimated marginal means

*. The mean difference is significant at the .05 level.

a. Adjustment for multiple comparisons: Bonferroni.

4.1.2 Total Errors

Descriptive Statistics

	DISPLAY	Mean	Std. Deviation	N
0	2D	.6036	.66395	8
	3D R	.2165	.61237	8
	ExoVis	.1768	.50000	8
	OI	.2500	.46291	8
	3D S	.0000	.00000	8
	Total	.2494	.51919	40
0.5	2D	.2500	.46291	8
	3D R	1.0089	.63889	8
	ExoVis	.1250	.35355	8
	OI	.1250	.35355	8
	3D S	.2500	.46291	8
	Total	.3518	.55586	40
1	2D	.4268	.60272	8
	3D R	.9053	.59076	8
	ExoVis	.4665	.68233	8
	OI	.0000	.00000	8
	3D S	.3536	.65465	8
	Total	.4304	.61162	40
1.5	2D	.8933	.81208	8
	3D R	1.2745	.65518	8
	ExoVis	.4268	.60272	8
	OI	.0000	.00000	8
	3D S	1.2745	.65518	8
	Total	.7738	.76875	40
2	2D	.6768	.78702	8
	3D R	.3750	.51755	8
	ExoVis	.1768	.50000	8
	OI	.1250	.35355	8
	3D S	1.0915	.79901	8
	Total	.4890	.68752	40

Mauchly's Test of Sphericity[b]

Measure: MEASURE_1

Within Subjects Effect	Mauchly's W	Approx. Chi-Square	df	Sig.	Epsilon[a] Greenhouse-Geisser	Huynh-Feldt	Lower-bound
HEIGHT	.486	24.077	9	.004	.747	.918	.250

Tests of Within-Subjects Effects

Measure: MEASURE_1

Source		df	F	Sig.	Partial Eta Squared	Observed Power[a]
HEIGHT	Sphericity Assumed	4	6.271	.000	.152	.987
	Greenhouse-Geisser	2.987	6.271	.001	.152	.960
	Huynh-Feldt	3.670	6.271	.000	.152	.981
	Lower-bound	1.000	6.271	.017	.152	.683
HEIGHT * DISPLAY	Sphericity Assumed	16	3.280	.000	.273	.999
	Greenhouse-Geisser	11.950	3.280	.000	.273	.993
	Huynh-Feldt	14.682	3.280	.000	.273	.998
	Lower-bound	4.000	3.280	.022	.273	.782
Error(HEIGHT)	Sphericity Assumed	140				
	Greenhouse-Geisser	104.6				
	Huynh-Feldt	128.5				
	Lower-bound	35.000				

a. Computed using alpha = .05

Tests of Between-Subjects Effects

Measure: MEASURE_1

Transformed Variable: Average

Source	df	F	Sig.	Partial Eta Squared	Observed Power[a]
Intercept	1	75.978	.000	.685	1.000
DISPLAY	4	5.083	.002	.367	.940
Error	35				

a. Computed using alpha = .05

Multiple Comparisons

Measure: MEASURE_1
Tukey HSD

(I) DISPLAY	(J) DISPLAY	Mean Difference (I-J)	Std. Error	Sig.	95% Confidence Interval	
					Lower Bound	Upper Bound
2D	3D R	-.1860	.1665	.796	-.6646	.2927
	ExoVis	.2957	.1665	.403	-.1829	.7743
	OI	.4701	.1665	.056	-.0086	.9487
	3D S	-.0238	.1665	1.000	-.5025	.4548
3D R	2D	.1860	.1665	.796	-.2927	.6646
	ExoVis	.4817*	.1665	.048	.0030	.9603
	OI	.6560*	.1665	.003	.1774	1.1347
	3D S	.1621	.1665	.865	-.3165	.6408
ExoVis	2D	-.2957	.1665	.403	-.7743	.1829
	3D R	-.4817*	.1665	.048	-.9603	-.0030
	OI	.1744	.1665	.831	-.3043	.6530
	3D S	-.3195	.1665	.326	-.7982	.1591
OI	2D	-.4701	.1665	.056	-.9487	.0086
	3D R	-.6560*	.1665	.003	-1.1347	-.1774
	ExoVis	-.1744	.1665	.831	-.6530	.3043
	3D S	-.4939*	.1665	.040	-.9725	-.0153
3D S	2D	.0238	.1665	1.000	-.4548	.5025
	3D R	-.1621	.1665	.865	-.6408	.3165
	ExoVis	.3195	.1665	.326	-.1591	.7982
	OI	.4939*	.1665	.040	.0153	.9725

Based on observed means.

*. The mean difference is significant at the .05 level.

Pairwise Comparisons

Measure: MEASURE_1

(I) HEIGHT	(J) HEIGHT	Mean Difference (I-J)	Std. Error	Sig.[a]	95% Confidence Interval for Difference[a]	
					Lower Bound	Upper Bound
.0	.5	-.102	.079	1.000	-.340	.135
	1.0	-.181	.096	.684	-.470	.107
	1.5	-.524*	.133	.004	-.922	-.127
	2.0	-.240	.113	.416	-.579	.100
.5	0	.102	.079	1.000	-.135	.340
	1.0	-.079	.105	1.000	-.395	.237
	1.5	-.422*	.107	.004	-.742	-.102
	2.0	-.137	.098	1.000	-.432	.157
1.0	0	.181	.096	.684	-.107	.470
	.5	.079	.105	1.000	-.237	.395
	1.5	-.343	.129	.118	-.731	.044
	2.0	-.059	.138	1.000	-.473	.356
1.5	0	.524*	.133	.004	.127	.922
	.5	.422*	.107	.004	.102	.742
	1.0	.343	.129	.118	-.044	.731
	2.0	.285	.103	.089	-.023	.593
2.0	0	.240	.113	.416	-.100	.579
	.5	.137	.098	1.000	-.157	.432
	1.0	.059	.138	1.000	-.356	.473
	1.5	-.285	.103	.089	-.593	.023

Based on estimated marginal means

*. The mean difference is significant at the .05 level.

a. Adjustment for multiple comparisons: Bonferroni.

Pairwise Comparisons

Measure: MEASURE_1

HEIGHT	(I) DISPLAY	(J) DISPLAY	Mean Difference (I-J)	Std. Error	Sig. [a]	95% Confidence Interval for Difference [a] Lower Bound	Upper Bound
.0	2D	3D R	.387	.253	1.000	-.371	1.145
		ExoVis	.427	.253	1.000	-.331	1.185
		OI	.354	.253	1.000	-.404	1.112
		3D S	.604	.253	.226	-.154	1.362
	3D R	2D	-.387	.253	1.000	-1.145	.371
		ExoVis	.040	.253	1.000	-.718	.798
		OI	-.033	.253	1.000	-.791	.724
		3D S	.217	.253	1.000	-.541	.974
	ExoVis	2D	-.427	.253	1.000	-1.185	.331
		3D R	-.040	.253	1.000	-.798	.718
		OI	-.073	.253	1.000	-.831	.685
		3D S	.177	.253	1.000	-.581	.935
	OI	2D	-.354	.253	1.000	-1.112	.404
		3D R	.033	.253	1.000	-.724	.791
		ExoVis	.073	.253	1.000	-.685	.831
		3D S	.250	.253	1.000	-.508	1.008
	3D S	2D	-.604	.253	.226	-1.362	.154
		3D R	-.217	.253	1.000	-.974	.541
		ExoVis	-.177	.253	1.000	-.935	.581
		OI	-.250	.253	1.000	-1.008	.508
.5	2D	3D R	-.759*	.233	.025	-1.457	-.060
		ExoVis	.125	.233	1.000	-.573	.823
		OI	.125	.233	1.000	-.573	.823
		3D S	.000	.233	1.000	-.698	.698
	3D R	2D	.759*	.233	.025	.060	1.457
		ExoVis	.884*	.233	.006	.185	1.582
		OI	.884*	.233	.006	.185	1.582
		3D S	.759*	.233	.025	.060	1.457
	ExoVis	2D	-.125	.233	1.000	-.823	.573
		3D R	-.884*	.233	.006	-1.582	-.185
		OI	.000	.233	1.000	-.698	.698
		3D S	-.125	.233	1.000	-.823	.573
	OI	2D	-.125	.233	1.000	-.823	.573
		3D R	-.884*	.233	.006	-1.582	-.185
		ExoVis	.000	.233	1.000	-.698	.698
		3D S	-.125	.233	1.000	-.823	.573
	3D S	2D	1.110E-16	.233	1.000	-.698	.698
		3D R	-.759*	.233	.025	-1.457	-.060
		ExoVis	.125	.233	1.000	-.573	.823
		OI	.125	.233	1.000	-.573	.823
1.0	2D	3D R	-.479	.283	1.000	-1.328	.371
		ExoVis	-.040	.283	1.000	-.889	.809
		OI	.427	.283	1.000	-.422	1.276
		3D S	.073	.283	1.000	-.776	.922
	3D R	2D	.479	.283	1.000	-.371	1.328
		ExoVis	.439	.283	1.000	-.410	1.288
		OI	.905*	.283	.030	.056	1.754
		3D S	.552	.283	.596	-.297	1.401
	ExoVis	2D	.040	.283	1.000	-.809	.889
		3D R	-.439	.283	1.000	-1.288	.410
		OI	.467	.283	1.000	-.383	1.316
		[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]

	OI	2D	-.427	.283	1.000	-1.276	.422
		3D R	-.905*	.283	.030	-1.754	-.056
		ExoVis	-.467	.283	1.000	-1.316	.383
		3D S	-.354	.283	1.000	-1.203	.496
	3D S	2D	-.073	.283	1.000	-.922	.776
		3D R	-.552	.283	.596	-1.401	.297
		ExoVis	-.113	.283	1.000	-.962	.736
		OI	.354	.283	1.000	-.496	1.203
1.5	2D	3D R	-.381	.307	1.000	-1.300	.538
		ExoVis	.467	.307	1.000	-.452	1.385
		OI	.893	.307	.062	-.026	1.812
		3D S	-.381	.307	1.000	-1.300	.538
	3D R	2D	.381	.307	1.000	-.538	1.300
		ExoVis	.848	.307	.090	-.071	1.767
		OI	1.275*	.307	.002	.356	2.193
		3D S	.000	.307	1.000	-.919	.919
	ExoVis	2D	-.467	.307	1.000	-1.385	.452
		3D R	-.848	.307	.090	-1.767	.071
		OI	.427	.307	1.000	-.492	1.346
		3D S	-.848	.307	.090	-1.767	.071
	OI	2D	-.893	.307	.062	-1.812	.026
		3D R	-1.275*	.307	.002	-2.193	-.356
		ExoVis	-.427	.307	1.000	-1.346	.492
		3D S	-1.275*	.307	.002	-2.193	-.356
	3D S	2D	.381	.307	1.000	-.538	1.300
		3D R	1.110E-16	.307	1.000	-.919	.919
		ExoVis	.848	.307	.090	-.071	1.767
		OI	1.275*	.307	.002	.356	2.193
2.0	2D	3D R	.302	.308	1.000	-.622	1.225
		ExoVis	.500	.308	1.000	-.424	1.424
		OI	.552	.308	.821	-.372	1.475
		3D S	-.415	.308	1.000	-1.338	.509
	3D R	2D	-.302	.308	1.000	-1.225	.622
		ExoVis	.198	.308	1.000	-.725	1.122
		OI	.250	.308	1.000	-.674	1.174
		3D S	-.717	.308	.260	-1.640	.207
	ExoVis	2D	-.500	.308	1.000	-1.424	.424
		3D R	-.198	.308	1.000	-1.122	.725
		OI	.052	.308	1.000	-.872	.975
		3D S	-.915	.308	.054	-1.838	.009
	OI	2D	-.552	.308	.821	-1.475	.372
		3D R	-.250	.308	1.000	-1.174	.674
		ExoVis	-.052	.308	1.000	-.975	.872
		3D S	-.967*	.308	.035	-1.890	-.043
	3D S	2D	.415	.308	1.000	-.509	1.338
		3D R	.717	.308	.260	-.207	1.640
		ExoVis	.915	.308	.054	-.009	1.838
		OI	.967*	.308	.035	.043	1.890

Based on estimated marginal means

*. The mean difference is significant at the .05 level.

a. Adjustment for multiple comparisons: Bonferroni.

Pairwise Comparisons

Measure: MEASURE_1

						95% Confidence Interval for Difference [a]	
DISPLAY	(I) HEIGHT	(J) HEIGHT	Mean Difference (I-J)	Std. Error	Sig. [a]	Lower Bound	Upper Bound
2D	.0	.5	.354	.177	.536	-.177	.884
		1.0	.177	.215	1.000	-.468	.822
		1.5	-.290	.297	1.000	-1.178	.599
		2.0	-.073	.253	1.000	-.832	.686
	.5	.0	-.354	.177	.536	-.884	.177
		1.0	-.177	.236	1.000	-.883	.530
		1.5	-.643	.239	.108	-1.359	.072
		2.0	-.427	.220	.602	-1.085	.232
	1.0	.0	-.177	.215	1.000	-.822	.468
		.5	.177	.236	1.000	-.530	.883
		1.5	-.467	.289	1.000	-1.333	.400
		2.0	-.250	.309	1.000	-1.177	.677
	1.5	.0	.290	.297	1.000	-.599	1.178
		.5	.643	.239	.108	-.072	1.359
		1.0	.467	.289	1.000	-.400	1.333
		2.0	.217	.230	1.000	-.473	.906
	2.0	.0	.073	.253	1.000	-.686	.832
		.5	.427	.220	.602	-.232	1.085
		1.0	.250	.309	1.000	-.677	1.177
		1.5	-.217	.230	1.000	-.906	.473
3D R	.0	.5	-.792*	.177	.001	-1.323	-.262
		1.0	-.689*	.215	.029	-1.334	-.044
		1.5	-1.058*	.297	.011	-1.946	-.170
		2.0	-.158	.253	1.000	-.918	.601
	.5	.0	.792*	.177	.001	.262	1.323
		1.0	.104	.236	1.000	-.603	.810
		1.5	-.266	.239	1.000	-.981	.450
		2.0	.634	.220	.067	-.024	1.292
	1.0	.0	.689*	.215	.029	.044	1.334
		.5	-.104	.236	1.000	-.810	.603
		1.5	-.369	.289	1.000	-1.235	.497
		2.0	.530	.309	.952	-.396	1.457
	1.5	.0	1.058*	.297	.011	.170	1.946
		.5	.266	.239	1.000	-.450	.981
		1.0	.369	.289	1.000	-.497	1.235
		2.0	.900*	.230	.004	.210	1.589
	2.0	.0	.158	.253	1.000	-.601	.918
		.5	-.634	.220	.067	-1.292	.024
		1.0	-.530	.309	.952	-1.457	.396
		1.5	-.900*	.230	.004	-1.589	-.210
ExoVis	.0	.5	.052	.177	1.000	-.479	.582
		1.0	-.290	.215	1.000	-.935	.355
		1.5	-.250	.297	1.000	-1.138	.638
		2.0	5.551E-17	.253	1.000	-.759	.759
	.5	.0	-.052	.177	1.000	-.582	.479
		1.0	-.342	.236	1.000	-1.048	.365
		1.5	-.302	.239	1.000	-1.017	.414
		2.0	-.052	.220	1.000	-.710	.607
	1.0	.0	.290	.215	1.000	-.355	.935
		.5	.342	.236	1.000	-.365	1.048
		1.5	.040	.289	1.000	-.826	.906
		2.0	.290	.309	1.000	-.637	1.216
	1.5	.0	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]

	1.5	.0	.250	.297	1.000	-.638	1.138
		.5	.302	.239	1.000	-.414	1.017
		1.0	-.040	.289	1.000	-.906	.826
		2.0	.250	.230	1.000	-.439	.939
	2.0	.0	.000	.253	1.000	-.759	.759
		.5	.052	.220	1.000	-.607	.710
		1.0	-.290	.309	1.000	-1.216	.637
		1.5	-.250	.230	1.000	-.939	.439
OI	.0	.5	.125	.177	1.000	-.405	.655
		1.0	.250	.215	1.000	-.395	.895
		1.5	.250	.297	1.000	-.638	1.138
		2.0	.125	.253	1.000	-.634	.884
	.5	.0	-.125	.177	1.000	-.655	.405
		1.0	.125	.236	1.000	-.582	.832
		1.5	.125	.239	1.000	-.591	.841
		2.0	.000	.220	1.000	-.658	.658
	1.0	.0	-.250	.215	1.000	-.895	.395
		.5	-.125	.236	1.000	-.832	.582
		1.5	.000	.289	1.000	-.866	.866
		2.0	-.125	.309	1.000	-1.052	.802
	1.5	.0	-.250	.297	1.000	-1.138	.638
		.5	-.125	.239	1.000	-.841	.591
		1.0	.000	.289	1.000	-.866	.866
		2.0	-.125	.230	1.000	-.814	.564
	2.0	.0	-.125	.253	1.000	-.884	.634
		.5	2.776E-17	.220	1.000	-.658	.658
		1.0	.125	.309	1.000	-.802	1.052
		1.5	.125	.230	1.000	-.564	.814
3D S	.0	.5	-.250	.177	1.000	-.780	.280
		1.0	-.354	.215	1.000	-.999	.292
		1.5	-1.275*	.297	.001	-2.163	-.386
		2.0	-1.092*	.253	.001	-1.851	-.332
	.5	.0	.250	.177	1.000	-.280	.780
		1.0	-.104	.236	1.000	-.810	.603
		1.5	-1.025*	.239	.001	-1.740	-.309
		2.0	-.842*	.220	.005	-1.500	-.183
	1.0	.0	.354	.215	1.000	-.292	.999
		.5	.104	.236	1.000	-.603	.810
		1.5	-.921*	.289	.030	-1.787	-.055
		2.0	-.738	.309	.226	-1.665	.189
	1.5	.0	1.275*	.297	.001	.386	2.163
		.5	1.025*	.239	.001	.309	1.740
		1.0	.921*	.289	.030	.055	1.787
		2.0	.183	.230	1.000	-.506	.872
	2.0	.0	1.092*	.253	.001	.332	1.851
		.5	.842*	.220	.005	.183	1.500
		1.0	**.738**	**.309**	**.226**	**-.189**	**1.665**
		1.5	-.183	.230	1.000	-.872	.506

Based on estimated marginal means

*. The mean difference is significant at the .05 level.

a. Adjustment for multiple comparisons: Bonferroni.

4.1.3 Error Size

Test Statistics[a,b]

	error_amt
Chi-Square	15.967
df	4
Asymp. Sig.	.003

a. Kruskal Wallis Test

b. Grouping Variable: display

2D & 3D R **Test Statistics[b]**

	error_amt
Mann-Whitney U	14.500
Wilcoxon W	42.500
Z	-.932
Asymp. Sig. (2-tailed)	.351
Exact Sig. [2*(1-tailed Sig.)]	.366[a]

a. Not corrected for ties.

b. Grouping Variable: display

2D & ExoVis **Test Statistics[b]**

	error_amt
Mann-Whitney U	13.500
Wilcoxon W	34.500
Z	-.280
Asymp. Sig. (2-tailed)	.780
Exact Sig. [2*(1-tailed Sig.)]	.792[a]

a. Not corrected for ties.

b. Grouping Variable: display

2D & OI **Test Statistics[b]**

	error_amt
Mann-Whitney U	1.500
Wilcoxon W	22.500
Z	-1.953
Asymp. Sig. (2-tailed)	.051
Exact Sig. [2*(1-tailed Sig.)]	.048[a]

a. Not corrected for ties.

b. Grouping Variable: display

2D & 3D S **Test Statistics[b]**

	error_amt
Mann-Whitney U	4.500
Wilcoxon W	40.500
Z	-2.792
Asymp. Sig. (2-tailed)	.005
Exact Sig. [2*(1-tailed Sig.)]	.008[a]

a. Not corrected for ties.

b. Grouping Variable: display

3D R & ExoVis **Test Statistics[b]**

	error_amt
Mann-Whitney U	12.000
Wilcoxon W	40.000
Z	-.900
Asymp. Sig. (2-tailed)	.368
Exact Sig. [2*(1-tailed Sig.)]	.432[a]

a. Not corrected for ties.

b. Grouping Variable: display

3D R & OI **Test Statistics[b]**

	error_amt
Mann-Whitney U	1.000
Wilcoxon W	29.000
Z	-2.172
Asymp. Sig. (2-tailed)	.030
Exact Sig. [2*(1-tailed Sig.)]	.033[a]

a. Not corrected for ties.

b. Grouping Variable: display

3D R & 3D S **Test Statistics**[b]

	error_amt
Mann-Whitney U	6.500
Wilcoxon W	42.500
Z	-2.702
Asymp. Sig. (2-tailed)	.007
Exact Sig. [2*(1-tailed Sig.)]	.009[a]

a. Not corrected for ties.

b. Grouping Variable: display

ExoVis & OI **Test Statistics**[b]

	error_amt
Mann-Whitney U	1.000
Wilcoxon W	16.000
Z	-1.986
Asymp. Sig. (2-tailed)	.047
Exact Sig. [2*(1-tailed Sig.)]	.071[a]

a. Not corrected for ties.

b. Grouping Variable: display

ExoVis & 3D S **Test Statistics**[b]

	error_amt
Mann-Whitney U	4.500
Wilcoxon W	40.500
Z	-2.592
Asymp. Sig. (2-tailed)	.010
Exact Sig. [2*(1-tailed Sig.)]	.019[a]

a. Not corrected for ties.

b. Grouping Variable: display

OI & 3D S **Test Statistics**[b]

	error_amt
Mann-Whitney U	.000
Wilcoxon W	36.000
Z	-2.837
Asymp. Sig. (2-tailed)	.005
Exact Sig. [2*(1-tailed Sig.)]	.012[a]

a. Not corrected for ties.

b. Grouping Variable: display

4.1.4 Rating Scale Data

Test Statistics[a,b]

	Difficulty	Mental Effort	Block Shape	Ball Position	Ball Height	Likeability
Chi-Square	13.163	8.941	12.171	10.400	6.677	17.243
df	4	4	4	4	4	4
Asymp. Sig.	.011	.063	.016	.034	.154	.002

a. Kruskal Wallis Test

b. Grouping Variable: group_num

Test Statistics[a,b]

	Confidence
Chi-Square	9.235
df	4
Asymp. Sig.	.055

a. Kruskal Wallis Test

b. Grouping Variable: GROUP

2D & 3D R

Test Statistics[b]

	Difficulty	Block Shape	Ball Position	Likeability
Mann-Whitney U	27.500	8.500	26.500	22.500
Wilcoxon W	63.500	44.500	62.500	58.500
Z	-.483	-2.518	-.597	-1.037
Asymp. Sig. (2-tailed)	.629	.012	.550	.300
Exact Sig. [2*(1-tailed Sig.)]	.645[a]	.010[a]	.574[a]	.328[a]

2D & ExoVis

Test Statistics[b]

	Difficulty	Block Shape	Ball Position	Likeability
Mann-Whitney U	13.500	7.000	18.500	3.500
Wilcoxon W	49.500	43.000	54.500	39.500
Z	-1.972	-2.690	-1.450	-3.061
Asymp. Sig. (2-tailed)	.049	.007	.147	.002
Exact Sig. [2*(1-tailed Sig.)]	.050[a]	.007[a]	.161[a]	.001[a]

2D & OI

Test Statistics[b]

	Difficulty	Block Shape	Ball Position	Likeability
Mann-Whitney U	9.000	6.000	11.500	4.500
Wilcoxon W	45.000	42.000	47.500	40.500
Z	-2.589	-2.797	-2.223	-2.961
Asymp. Sig. (2-tailed)	.010	.005	.026	.003
Exact Sig. [2*(1-tailed Sig.)]	.015[a]	.005[a]	.028[a]	.002[a]

2D & 3D S

Test Statistics[b]

	Difficulty	Block Shape	Ball Position	Likeability
Mann-Whitney U	17.500	9.000	17.000	15.500
Wilcoxon W	53.500	45.000	53.000	51.500
Z	-1.556	-2.469	-1.659	-1.810
Asymp. Sig. (2-tailed)	.120	.014	.097	.070
Exact Sig. [2*(1-tailed Sig.)]	.130[a]	.015[a]	.130[a]	.083[a]

a. Not corrected for ties.

b. Grouping Variable: group_num

3D R & ExoVis

Test Statistics[b]

	Difficulty	Block Shape	Ball Position	Likeability
Mann-Whitney U	12.000	29.000	17.500	8.500
Wilcoxon W	48.000	65.000	53.500	44.500
Z	-2.129	-.324	-1.576	-2.522
Asymp. Sig. (2-tailed)	.033	.746	.115	.012
Exact Sig. [2*(1-tailed Sig.)]	.038[a]	.798[a]	.130[a]	.010[a]

3D R & OI

Test Statistics[b]

	Difficulty	Block Shape	Ball Position	Likeability
Mann-Whitney U	6.000	24.000	8.500	13.000
Wilcoxon W	42.000	60.000	44.500	49.000
Z	-2.864	-.865	-2.534	-2.065
Asymp. Sig. (2-tailed)	.004	.387	.011	.039
Exact Sig. [2*(1-tailed Sig.)]	.005[a]	.442[a]	.010[a]	.050[a]

3D R & 3D S

Test Statistics[b]

	Difficulty	Block Shape	Ball Position	Likeability
Mann-Whitney U	14.500	30.500	10.000	27.500
Wilcoxon W	50.500	66.500	46.000	63.500
Z	-1.880	-.163	-2.414	-.497
Asymp. Sig. (2-tailed)	.060	.871	.016	.619
Exact Sig. [2*(1-tailed Sig.)]	.065[a]	.878[a]	.021[a]	.645[a]

ExoVis & OI

Test Statistics[b]

	Difficulty	Block Shape	Ball Position	Likeability
Mann-Whitney U	25.500	27.500	27.500	25.000
Wilcoxon W	61.500	63.500	63.500	61.000
Z	-.733	-.489	-.498	-.764
Asymp. Sig. (2-tailed)	.464	.625	.619	.445
Exact Sig. [2*(1-tailed Sig.)]	.505[a]	.645[a]	.645[a]	.505[a]

a. Not corrected for ties.

b. Grouping Variable: group_num

ExoVis & 3D S

Test Statistics[b]

	Difficulty	Block Shape	Ball Position	Likeability
Mann-Whitney U	26.000	28.000	28.500	10.500
Wilcoxon W	62.000	64.000	64.500	46.500
Z	-.652	-.433	-.385	-2.324
Asymp. Sig. (2-tailed)	.514	.665	.701	.020
Exact Sig. [2*(1-tailed Sig.)]	.574[a]	.721[a]	.721[a]	.021[a]

OI & 3D S

Test Statistics[b]

	Difficulty	Block Shape	Ball Position	Likeability
Mann-Whitney U	16.000	22.500	22.500	16.000
Wilcoxon W	52.000	58.500	58.500	52.000
Z	-1.771	-1.029	-1.057	-1.767
Asymp. Sig. (2-tailed)	.077	.303	.291	.077
Exact Sig. [2*(1-tailed Sig.)]	.105[a]	.328[a]	.328[a]	.105[a]

a. Not corrected for ties.

b. Grouping Variable: group_num

4.2 Orientation Task

Key: 2D = 2D display, 3D = 3D display, OI = orientation icon, In-place = clip plane display. TRIATYPE = Trial type (Side, Top, or Other).

4.2.1 Timing Data

Descriptive Statistics

	DISPLAY	Mean	Std. Deviation	N
Side	2D	3.3913	.35454	8
	3D	2.7963	.37006	8
	ExoVis	3.0688	.59316	8
	OI	3.3063	.29957	8
	In-place	3.4450	.48600	8
	Total	3.2015	.47738	40
Top	2D	3.1575	.36456	8
	3D	2.8175	.64258	8
	ExoVis	3.0925	.70014	8
	OI	3.5863	.36975	8
	In-place	3.9713	.39815	8
	Total	3.3250	.63897	40
Other	2D	3.3938	.38441	8
	3D	3.1575	.53197	8
	ExoVis	3.1225	.54245	8
	OI	3.4163	.38079	8
	In-place	3.6713	.38365	8
	Total	3.3523	.47249	40

Mauchly's Test of Sphericity[b]

Measure: MEASURE_1

					Epsilon[a]		
Within Subjects Effect	Mauchly's W	Approx. Chi-Square	df	Sig.	Greenhouse -Geisser	Huynh -Feldt	Lower-bound
TRIATYPE	.798	7.686	2	.021	.832	.968	.500

Tests of Within-Subjects Effects

Measure: MEASURE_1

Source		df	F	Sig.	Partial Eta Squared	Observed Power[a]
TRIATYPE	Sphericity Assumed	2	4.943	.010	.124	.793
	Greenhouse-Geisser	1.663	4.943	.015	.124	.735
	Huynh-Feldt	1.936	4.943	.011	.124	.783
	Lower-bound	1.000	4.943	.033	.124	.580
TRIATYPE * DISPLAY	Sphericity Assumed	8	4.502	.000	.340	.994
	Greenhouse-Geisser	6.654	4.502	.001	.340	.984
	Huynh-Feldt	7.744	4.502	.000	.340	.992
	Lower-bound	4.000	4.502	.005	.340	.907
Error(TRIATYPE)	Sphericity Assumed	70				
	Greenhouse-Geisser	58.22				
	Huynh-Feldt	67.76				
	Lower-bound	35.00				

a. Computed using alpha = .05

Tests of Between-Subjects Effects

Measure: MEASURE_1

Transformed Variable: Average

Source	df	F	Sig.	Partial Eta Squared	Observed Power[a]
Intercept	1	2351.6	.000	.985	1.000
DISPLAY	4	3.892	.010	.308	.855
Error	35				

a. Computed using alpha = .05

Multiple Comparisons

Measure: MEASURE_1
Tukey HSD

(I) DISPLAY	(J) DISPLAY	Mean Difference (I-J)	Std. Error	Sig.	95% Confidence Interval Lower Bound	95% Confidence Interval Upper Bound
2D	3D	.3904	.2147	.380	-.2270	1.0078
	ExoVis	.2196	.2147	.843	-.3978	.8370
	OI	-.1221	.2147	.979	-.7395	.4953
	In-place	-.3817	.2147	.402	-.9990	.2357
3D	2D	-.3904	.2147	.380	-1.0078	.2270
	ExoVis	-.1708	.2147	.930	-.7882	.4465
	OI	-.5125	.2147	.143	-1.1299	.1049
	In-place	-.7721*	.2147	.008	-1.3895	-.1547
ExoVis	2D	-.2196	.2147	.843	-.8370	.3978
	3D	.1708	.2147	.930	-.4465	.7882
	OI	-.3417	.2147	.513	-.9590	.2757
	In-place	-.6012	.2147	.059	-1.2186	.0161
OI	2D	.1221	.2147	.979	-.4953	.7395
	3D	.5125	.2147	.143	-.1049	1.1299
	ExoVis	.3417	.2147	.513	-.2757	.9590
	In-place	-.2596	.2147	.746	-.8770	.3578
In-place	2D	.3817	.2147	.402	-.2357	.9990
	3D	.7721*	.2147	.008	.1547	1.3895
	ExoVis	.6012	.2147	.059	-.0161	1.2186
	OI	.2596	.2147	.746	-.3578	.8770

Based on observed means.

*. The mean difference is significant at the .05 level.

Pairwise Comparisons

Measure: MEASURE_1

(I) TRIATYPE	(J) TRIATYPE	Mean Difference (I-J)	Std. Error	Sig.[a]	95% Confidence Interval for Difference[a] Lower Bound	95% Confidence Interval for Difference[a] Upper Bound
Side	Top	-.123	.061	.152	-.277	.030
	Other	-.151*	.049	.012	-.274	-.028
Top	Side	.123	.061	.152	-.030	.277
	Other	-.027	.041	1.0	-.131	.077
Other	Side	.151*	.049	.012	.028	.274
	Top	.027	.041	1.0	-.077	.131

Based on estimated marginal means

*. The mean difference is significant at the .05 level.

a. Adjustment for multiple comparisons: Bonferroni.

Appendix 3: Statistical Details

Pairwise Comparisons

Measure: MEASURE_1

TRIATYPE	(I) DISPLAY	(J) DISPLAY	Mean Difference (I-J)	Std. Error	Sig. [a]	95% Confidence Interval for Difference [a] Lower Bound	Upper Bound
Side	2D	3D	.595	.217	.095	-.055	1.245
		ExoVis	.323	.217	1.000	-.327	.972
		OI	.085	.217	1.000	-.565	.735
		In-place	-.054	.217	1.000	-.703	.596
	3D	2D	-.595	.217	.095	-1.245	.055
		ExoVis	-.272	.217	1.000	-.922	.377
		OI	-.510	.217	.244	-1.160	.140
		In-place	-.649	.217	.051	-1.298	.001
	ExoVis	2D	-.323	.217	1.000	-.972	.327
		3D	.272	.217	1.000	-.377	.922
		OI	-.238	.217	1.000	-.887	.412
		In-place	-.376	.217	.915	-1.026	.273
	OI	2D	-.085	.217	1.000	-.735	.565
		3D	.510	.217	.244	-.140	1.160
		ExoVis	.238	.217	1.000	-.412	.887
		In-place	-.139	.217	1.000	-.788	.511
	In-place	2D	.054	.217	1.000	-.596	.703
		3D	.649	.217	.051	-.001	1.298
		ExoVis	.376	.217	.915	-.273	1.026
		OI	.139	.217	1.000	-.511	.788
Top	2D	3D	.340	.258	1.000	-.433	1.113
		ExoVis	.065	.258	1.000	-.708	.838
		OI	-.429	.258	1.000	-1.202	.344
		In-place	-.814*	.258	.033	-1.587	-.041
	3D	2D	-.340	.258	1.000	-1.113	.433
		ExoVis	-.275	.258	1.000	-1.048	.498
		OI	-.769	.258	.052	-1.542	.004
		In-place	-1.154*	.258	.001	-1.927	-.381
	ExoVis	2D	-.065	.258	1.000	-.838	.708
		3D	.275	.258	1.000	-.498	1.048
		OI	-.494	.258	.639	-1.267	.279
		In-place	-.879*	.258	.017	-1.652	-.106
	OI	2D	.429	.258	1.000	-.344	1.202
		3D	.769	.258	.052	-.004	1.542
		ExoVis	.494	.258	.639	-.279	1.267
		In-place	-.385	.258	1.000	-1.158	.388
	In-place	2D	.814*	.258	.033	.041	1.587
		3D	1.154*	.258	.001	.381	1.927
		ExoVis	.879*	.258	.017	.106	1.652
		OI	.385	.258	1.000	-.388	1.158
Other	2D	3D	.236	.226	1.000	-.439	.912
		ExoVis	.271	.226	1.000	-.404	.947
		OI	-.023	.226	1.000	-.698	.653
		In-place	-.277	.226	1.000	-.953	.398
	3D	2D	-.236	.226	1.000	-.912	.439
		ExoVis	.035	.226	1.000	-.641	.711
		OI	-.259	.226	1.000	-.934	.417
		In-place	-.514	.226	.289	-1.189	.162
	ExoVis	2D	-.271	.226	1.000	-.947	.404
		3D	-.035	.226	1.000	-.711	.641
		OI	-.294	.226	1.000	-.969	.382
		In-place	-.549	.226	.202	-1.224	.127
	OI	2D	.023	.226	1.000	-.653	.698
		3D	.259	.226	1.000	-.417	.934
		ExoVis	.294	.226	1.000	-.382	.969
		In-place	-.255	.226	1.000	-.931	.421
	In-place	2D	.277	.226	1.000	-.398	.953
		3D	.514	.226	.289	-.162	1.189
		ExoVis	.549	.226	.202	-.127	1.224
		OI	.255	.226	1.000	-.421	.931

Pairwise Comparisons

Measure: MEASURE_1

DISPLAY	(I) TRIATYPE	(J) TRIATYPE	Mean Difference (I-J)	Std. Error	Sig.[a]	95% Confidence Interval for Difference[a] Lower Bound	Upper Bound
2D	Side	Top	.234	.136	.286	-.109	.577
		Other	-.002	.109	1.000	-.278	.273
	Top	Side	-.234	.136	.286	-.577	.109
		Other	-.236*	.093	.046	-.469	-.003
	Other	Side	.002	.109	1.000	-.273	.278
		Top	.236*	.093	.046	.003	.469
3D	Side	Top	-.021	.136	1.000	-.364	.322
		Other	-.361*	.109	.007	-.636	-.086
	Top	Side	.021	.136	1.000	-.322	.364
		Other	-.340*	.093	.002	-.573	-.107
	Other	Side	.361*	.109	.007	.086	.636
		Top	.340*	.093	.002	.107	.573
ExoVis	Side	Top	-.024	.136	1.000	-.367	.319
		Other	-.054	.109	1.000	-.329	.221
	Top	Side	.024	.136	1.000	-.319	.367
		Other	-.030	.093	1.000	-.263	.203
	Other	Side	.054	.109	1.000	-.221	.329
		Top	.030	.093	1.000	-.203	.263
OI	Side	Top	-.280	.136	.143	-.623	.063
		Other	-.110	.109	.965	-.385	.165
	Top	Side	.280	.136	.143	-.063	.623
		Other	.170	.093	.226	-.063	.403
	Other	Side	.110	.109	.965	-.165	.385
		Top	-.170	.093	.226	-.403	.063
In-place	Side	Top	-.526*	.136	.001	-.869	-.183
		Other	-.226	.109	.139	-.501	.049
	Top	Side	.526*	.136	.001	.183	.869
		Other	.300*	.093	.008	.067	.533
	Other	Side	.226	.109	.139	-.049	.501
		Top	-.300*	.093	.008	-.533	-.067

Based on estimated marginal means

*. The mean difference is significant at the .05 level.

a. Adjustment for multiple comparisons: Bonferroni.

4.2.2 Errors

Descriptive Statistics

	DISPLAY	Mean	Std. Deviation	N
Side	2D	.5719	.27756	8
	3D	.7500	.60804	8
	ExoVis	.9171	.40858	8
	OI	.4602	.41379	8
	In-place	.8997	.38480	8
	Total	.7198	.44787	40
Top	2D	.6904	.52777	8
	3D	1.7742	.47735	8
	ExoVis	1.0062	.56485	8
	OI	.6645	.40977	8
	In-place	1.3995	.56124	8
	Total	1.1069	.64927	40
Other	2D	.7506	.28472	8
	3D	1.5241	.45149	8
	ExoVis	.8820	.28930	8
	OI	.4822	.15778	8
	In-place	1.2401	.52519	8
	Total	.9758	.50825	40

Mauchly's Test of Sphericity[b]

Measure: MEASURE_1

					Epsilon[a]		
Within Subjects Effect	Mauchly's W	Approx. Chi-Square	df	Sig.	Greenhouse -Geisser	Huynh-Feldt	Lower-bound
TRIATYPE	.953	1.620	2	.445	.956	1.000	.500

Tests of Within-Subjects Effects

Measure: MEASURE_1

Source		df	F	Sig.	Partial Eta Squared	Observed Power[a]
TRIATYPE	Sphericity Assumed	2	15.4	.000	.305	.999
	Greenhouse-Geisser	1.9	15.4	.000	.305	.999
	Huynh-Feldt	2.0	15.4	.000	.305	.999
	Lower-bound	1.0	15.4	.000	.305	.968
TRIATYPE * DISPLAY	Sphericity Assumed	8	3.591	.002	.291	.973
	Greenhouse-Geisser	7.6	3.591	.002	.291	.968
	Huynh-Feldt	8.0	3.591	.002	.291	.973
	Lower-bound	4.0	3.591	.015	.291	.822
Error(TRIATYPE)	Sphericity Assumed	70				
	Greenhouse-Geisser	67				
	Huynh-Feldt	70				
	Lower-bound	35				

a. Computed using alpha = .05

Tests of Between-Subjects Effects

Measure: MEASURE_1

Transformed Variable: Average

Source	df	F	Sig.	Partial Eta Squared	Observed Power[a]
Intercept	1	275.5	.000	.887	1.000
DISPLAY	4	7.275	.000	.454	.990
Error	35				

a. Computed using alpha = .05

Multiple Comparisons

Measure: MEASURE_1
Tukey HSD

(I) DISPLAY	(J) DISPLAY	Mean Difference (I-J)	Std. Error	Sig.	95% Confidence Interval	
					Lower Bound	Upper Bound
2D	3D	-.6785*	.17797	.005	-1.1902	-.1668
	ExoVis	-.2641	.17797	.579	-.7758	.2476
	OI	.1354	.17797	.940	-.3763	.6470
	In-place	-.5088	.17797	.052	-1.0205	.0029
3D	2D	.6785*	.17797	.005	.1668	1.1902
	ExoVis	.4143	.17797	.160	-.0973	.9260
	OI	.8138*	.17797	.001	.3021	1.3255
	In-place	.1697	.17797	.874	-.3420	.6813
ExoVis	2D	.2641	.17797	.579	-.2476	.7758
	3D	-.4143	.17797	.160	-.9260	.0973
	OI	.3995	.17797	.188	-.1122	.9112
	In-place	-.2447	.17797	.647	-.7564	.2670
OI	2D	-.1354	.17797	.940	-.6470	.3763
	3D	-.8138*	.17797	.001	-1.3255	-.3021
	ExoVis	-.3995	.17797	.188	-.9112	.1122
	In-place	-.6442*	.17797	.008	-1.1558	-.1325
In-place	2D	.5088	.17797	.052	-.0029	1.0205
	3D	-.1697	.17797	.874	-.6813	.3420
	ExoVis	.2447	.17797	.647	-.2670	.7564
	OI	.6442*	.17797	.008	.1325	1.1558

Based on observed means.

*. The mean difference is significant at the .05 level.

Pairwise Comparisons

Measure: MEASURE_1

(I) TRIATYPE	(J) TRIATYPE	Mean Difference (I-J)	Std. Error	Sig.[a]	95% Confidence Interval for Difference[a]	
					Lower Bound	Upper Bound
Side	Top	-.387*	.078	.000	-.583	-.191
	Other	-.256*	.065	.001	-.420	-.092
Top	Side	.387*	.078	.000	.191	.583
	Other	.131	.070	.203	-.044	.306
Other	Side	.256*	.065	.001	.092	.420
	Top	-.131	.070	.203	-.306	.044

Based on estimated marginal means

*. The mean difference is significant at the .05 level.

a. Adjustment for multiple comparisons: Bonferroni.

Pairwise Comparisons

Measure: MEASURE_1

TRIATYPE	(I) DISPLAY	(J) DISPLAY	Mean Difference (I-J)	Std. Error	Sig. [a]	95% Confidence Interval for Difference [a]	
						Lower Bound	Upper Bound
Side	2D	3D	-.178	.216	1.000	-.825	.469
		ExoVis	-.345	.216	1.000	-.992	.302
		OI	.112	.216	1.000	-.535	.759
		In-place	-.328	.216	1.000	-.975	.319
	3D	2D	.178	.216	1.000	-.469	.825
		ExoVis	-.167	.216	1.000	-.814	.480
		OI	.290	.216	1.000	-.357	.937
		In-place	-.150	.216	1.000	-.797	.497
	ExoVis	2D	.345	.216	1.000	-.302	.992
		3D	.167	.216	1.000	-.480	.814
		OI	.457	.216	.416	-.190	1.104
		In-place	.017	.216	1.000	-.630	.664
	OI	2D	-.112	.216	1.000	-.759	.535
		3D	-.290	.216	1.000	-.937	.357
		ExoVis	-.457	.216	.416	-1.104	.190
		In-place	-.440	.216	.495	-1.087	.208
	In-place	2D	.328	.216	1.000	-.319	.975
		3D	.150	.216	1.000	-.497	.797
		ExoVis	-.017	.216	1.000	-.664	.630
		OI	.440	.216	.495	-.208	1.087
Top	2D	3D	-1.084*	.256	.002	-1.850	-.318
		ExoVis	-.316	.256	1.000	-1.082	.451
		OI	.026	.256	1.000	-.740	.792
		In-place	-.709	.256	.089	-1.475	.057
	3D	2D	1.084*	.256	.002	.318	1.850
		ExoVis	.768*	.256	.049	.002	1.534
		OI	1.110*	.256	.001	.343	1.876
		In-place	.376	.256	1.000	-.392	1.141
	ExoVis	2D	.316	.256	1.000	-.451	1.082
		3D	-.768*	.256	.049	-1.534	-.002
		OI	.342	.256	1.000	-.425	1.108
		In-place	-.393	.256	1.000	-1.160	.373
	OI	2D	-.026	.256	1.000	-.792	.740
		3D	-1.110*	.256	.001	-1.876	-.343
		ExoVis	-.342	.256	1.000	-1.108	.425
		In-place	-.735	.256	.069	-1.501	.031
	In-place	2D	.709	.256	.089	-.057	1.475
		3D	-.375	.256	1.000	-1.141	.392
		ExoVis	.393	.256	1.000	-.373	1.160
		OI	.735	.256	.069	-.031	1.501
Other	2D	3D	-.773*	.183	.002	-1.322	-.225
		ExoVis	-.131	.183	1.000	-.679	.417
		OI	.268	.183	1.000	-.280	.817
		In-place	-.489	.183	.113	-1.038	.059
	3D	2D	.773*	.183	.002	.225	1.322
		ExoVis	.642*	.183	.013	.094	1.190
		OI	1.042*	.183	.000	.494	1.590
		In-place	.284	.183	1.000	-.264	.832
	ExoVis	2D	.131	.183	1.000	-.417	.679
		3D	-.642*	.183	.013	-1.190	-.094
		OI	.400	.183	.356	-.148	.948
		In-place	-.358	.183	.583	-.906	.190
	OI	2D	-.268	.183	1.000	-.817	.280
		3D	-1.042*	.183	.000	-1.590	-.494
		ExoVis	-.400	.183	.356	-.948	.148
		In-place	-.758*	.183	.002	-1.306	-.210
	In-place	2D	.489	.183	.113	-.059	1.038
		3D	-.284	.183	1.000	-.832	.264
		ExoVis	.358	.183	.583	-.190	.906
		OI	.758*	.183	.002	.210	1.306

Pairwise Comparisons

Measure: MEASURE_1

DISPLAY	(I) TRIATYPE	(J) TRIATYPE	Mean Difference (I-J)	Std. Error	Sig.[a]	95% Confidence Interval for Difference[a] Lower Bound	Upper Bound
2D	Side	Top	-.118	.174	1.00	-.557	.320
		Other	-.179	.145	.682	-.544	.187
	Top	Side	.118	.174	1.00	-.320	.557
		Other	-.060	.156	1.00	-.451	.331
	Other	Side	.179	.145	.682	-.187	.544
		Top	.060	.156	1.00	-.331	.451
3D	Side	Top	-1.024*	.174	.000	-1.463	-.586
		Other	-.774*	.145	.000	-1.140	-.408
	Top	Side	1.024*	.174	.000	.586	1.463
		Other	.250	.156	.350	-.141	.641
	Other	Side	.774*	.145	.000	.408	1.140
		Top	-.250	.156	.350	-.641	.141
ExoVis	Side	Top	-.089	.174	1.00	-.528	.349
		Other	.035	.145	1.00	-.331	.401
	Top	Side	.089	.174	1.00	-.349	.528
		Other	.124	.156	1.00	-.267	.515
	Other	Side	-.035	.145	1.00	-.401	.331
		Top	-.124	.156	1.00	-.515	.267
OI	Side	Top	-.204	.174	.748	-.643	.234
		Other	-.022	.145	1.00	-.388	.344
	Top	Side	.204	.174	.748	-.234	.643
		Other	.182	.156	.747	-.209	.573
	Other	Side	.022	.145	1.00	-.344	.388
		Top	-.182	.156	.747	-.573	.209
In-place	Side	Top	-.500*	.174	.021	-.938	-.061
		Other	-.340	.145	.075	-.706	.025
	Top	Side	.500*	.174	.021	.061	.938
		Other	.159	.156	.938	-.232	.551
	Other	Side	.340	.145	.075	-.025	.706
		Top	-.159	.156	.938	-.551	.232

Based on estimated marginal means

*. The mean difference is significant at the .05 level.

a. Adjustment for multiple comparisons: Bonferroni.

4.2.3 Ability to Predict Error (Estimated Error - Actual Error)

Descriptive Statistics

	DISPLAY	Mean	Std. Deviation	N
Side	2D	2.8197	2.36545	8
	3D	-.2241	2.26876	8
	ExoVis	.1472	1.37497	8
	OI	1.7251	1.90701	8
	In-place	.7771	4.60562	8
	Total	1.0490	2.82469	40
Top	2D	1.9562	2.18193	8
	3D	-3.9097	3.96814	8
	ExoVis	.5225	1.82561	8
	OI	2.1365	2.04016	8
	In-place	.4872	6.20684	8
	Total	.2385	4.10414	40
Other	2D	2.8075	1.94958	8
	3D	-1.3949	2.70377	8
	ExoVis	.5393	1.51116	8
	OI	2.4248	1.76321	8
	In-place	.1769	5.16120	8
	Total	.9107	3.19073	40

Mauchly's Test of Sphericity[b]

Measure: MEASURE_1

					Epsilon[a]		
Within Subjects Effect	Mauchly's W	Approx. Chi-Square	df	Sig.	Greenhouse -Geisser	Huynh-Feldt	Lower-bound
TRIATYPE	.851	5.487	2	.064	.870	1.000	.500

Appendix 3: Statistical Details

Tests of Within-Subjects Effects

Measure: MEASURE_1

Source		df	F	Sig.	Partial Eta Squared	Observed Power[a]
TRIATYPE	Sphericity Assumed	2	4.544	.014	.115	.756
	Greenhouse-Geisser	1.741	4.544	.018	.115	.712
	Huynh-Feldt	2.000	4.544	.014	.115	.756
	Lower-bound	1.000	4.544	.040	.115	.545
TRIATYPE * DISPLAY	Sphericity Assumed	8	3.765	.001	.301	.979
	Greenhouse-Geisser	6.962	3.765	.002	.301	.964
	Huynh-Feldt	8.000	3.765	.001	.301	.979
	Lower-bound	4.000	3.765	.012	.301	.842
Error(TRIATYPE)	Sphericity Assumed	70				
	Greenhouse-Geisser	60.92				
	Huynh-Feldt	70.00				
	Lower-bound	35.00				

a. Computed using alpha = .05

Tests of Between-Subjects Effects

Measure: MEASURE_1

Transformed Variable: Average

Source	df	F	Sig.	Partial Eta Squared	Observed Power[a]
Intercept	1	2.467	.125	.066	.333
DISPLAY	4	2.730	.045	.238	.693
Error	35				

a. Computed using alpha = .05

Multiple Comparisons

Measure: MEASURE_1
Tukey HSD

(I) DISPLAY	(J) DISPLAY	Mean Difference (I-J)	Std. Error	Sig.	95% Confidence Interval	
					Lower Bound	Upper Bound
2D	3D	4.3707*	1.475	.041	.1289	8.6125
	ExoVis	2.1248	1.475	.607	-2.1170	6.3666
	OI	.4324	1.475	.998	-3.8094	4.6742
	In-place	2.0474	1.475	.639	-2.1944	6.2892
3D	2D	-4.3707*	1.475	.041	-8.6125	-.1289
	ExoVis	-2.2459	1.475	.555	-6.4877	1.9959
	OI	-3.9383	1.475	.079	-8.1802	.3035
	In-place	-2.3233	1.475	.523	-6.5651	1.9185
ExoVis	2D	-2.1248	1.475	.607	-6.3666	2.1170
	3D	2.2459	1.475	.555	-1.9959	6.4877
	OI	-1.6924	1.475	.781	-5.9342	2.5494
	In-place	-.0774	1.475	1.00	-4.3192	4.1644
OI	2D	-.4324	1.475	.998	-4.6742	3.8094
	3D	3.9383	1.475	.079	-.3035	8.1802
	ExoVis	1.6924	1.475	.781	-2.5494	5.9342
	In-place	1.6151	1.475	.808	-2.6267	5.8569
In-place	2D	-2.0474	1.475	.639	-6.2892	2.1944
	3D	2.3233	1.475	.523	-1.9185	6.5651
	ExoVis	.0774	1.475	1.00	-4.1644	4.3192
	OI	-1.6151	1.475	.808	-5.8569	2.6267

Based on observed means.

*. The mean difference is significant at the .05 level.

Pairwise Comparisons

Measure: MEASURE_1

(I) TRIATYPE	(J) TRIATYPE	Mean Difference (I-J)	Std. Error	Sig.[a]	95% Confidence Interval for Difference[a]	
					Lower Bound	Upper Bound
Side	Top	.810	.325	.052	-.007	1.627
	Other	.138	.228	1.000	-.435	.712
Top	Side	-.810	.325	.052	-1.627	.007
	Other	-.672	.301	.096	-1.429	.085
Other	Side	-.138	.228	1.000	-.712	.435
	Top	.672	.301	.096	-.085	1.429

Based on estimated marginal means

a. Adjustment for multiple comparisons: Bonferroni.

Pairwise Comparisons

Measure: MEASURE_1

TRIATYPE	(I) DISPLAY	(J) DISPLAY	Mean Difference (I-J)	Std. Error	Sig.[a]	95% Confidence Interval for Difference[a] Lower Bound	Upper Bound
Side	2D	3D	3.044	1.369	.327	-1.058	7.145
		ExoVis	2.673	1.369	.589	-1.429	6.774
		OI	1.095	1.369	1.000	-3.007	5.196
		In-place	2.043	1.369	1.000	-2.059	6.144
	3D	2D	-3.044	1.369	.327	-7.145	1.058
		ExoVis	-.371	1.369	1.000	-4.473	3.730
		OI	-1.949	1.369	1.000	-6.051	2.152
		In-place	-1.001	1.369	1.000	-5.103	3.100
	ExoVis	2D	-2.673	1.369	.589	-6.774	1.429
		3D	.371	1.369	1.000	-3.730	4.473
		OI	-1.578	1.369	1.000	-5.679	2.524
		In-place	-.630	1.369	1.000	-4.731	3.472
	OI	2D	-1.095	1.369	1.000	-5.196	3.007
		3D	1.949	1.369	1.000	-2.152	6.051
		ExoVis	1.578	1.369	1.000	-2.524	5.679
		In-place	.948	1.369	1.000	-3.154	5.049
	In-place	2D	-2.043	1.369	1.000	-6.144	2.059
		3D	1.001	1.369	1.000	-3.100	5.103
		ExoVis	.630	1.369	1.000	-3.472	4.731
		OI	-.948	1.369	1.000	-5.049	3.154
Top	2D	3D	5.866*	1.824	.028	.402	11.330
		ExoVis	1.434	1.824	1.000	-4.031	6.898
		OI	-.180	1.824	1.000	-5.644	5.284
		In-place	1.469	1.824	1.000	-3.995	6.933
	3D	2D	-5.866*	1.824	.028	-11.330	-.402
		ExoVis	-4.432	1.824	.204	-9.897	1.032
		OI	-6.046*	1.824	.021	-11.510	-.582
		In-place	-4.397	1.824	.213	-9.861	1.067
	ExoVis	2D	-1.434	1.824	1.000	-6.898	4.031
		3D	4.432	1.824	.204	-1.032	9.897
		OI	-1.614	1.824	1.000	-7.078	3.850
		In-place	.035	1.824	1.000	-5.429	5.500
	OI	2D	.180	1.824	1.000	-5.284	5.644
		3D	6.046*	1.824	.021	.582	11.510
		ExoVis	1.614	1.824	1.000	-3.850	7.078
		In-place	1.649	1.824	1.000	-3.815	7.114
	In-place	2D	-1.469	1.824	1.000	-6.933	3.995
		3D	4.397	1.824	.213	-1.067	9.861
		ExoVis	-.035	1.824	1.000	-5.500	5.429
		OI	-1.649	1.824	1.000	-7.114	3.815
Other	2D	3D	4.202	1.469	.071	-.198	8.603
		ExoVis	2.268	1.469	1.000	-2.132	6.668
		OI	.383	1.469	1.000	-4.018	4.783
		In-place	2.631	1.469	.819	-1.770	7.031
	3D	2D	-4.202	1.469	.071	-8.603	.198
		ExoVis	-1.934	1.469	1.000	-6.334	2.466
		OI	-3.820	1.469	.135	-8.220	.581
		In-place	-1.572	1.469	1.000	-5.972	2.829
	ExoVis	2D	-2.268	1.469	1.000	-6.668	2.132
		3D	1.934	1.469	1.000	-2.466	6.334
		OI	-1.885	1.469	1.000	-6.286	2.515
		In-place	.362	1.469	1.000	-4.038	4.763
	OI	2D	-.383	1.469	1.000	-4.783	4.018
		3D	3.820	1.469	.135	-.581	8.220
		ExoVis	1.885	1.469	1.000	-2.515	6.286
		In-place	2.248	1.469	1.000	-2.152	6.648
	In-place	2D	-2.631	1.469	.819	-7.031	1.770
		3D	1.572	1.469	1.000	-2.829	5.972
		ExoVis	-.362	1.469	1.000	-4.763	4.038
		OI	-2.248	1.469	1.000	-6.648	2.152

Pairwise Comparisons

Measure: MEASURE_1

DISPLAY	(I) TRIATYPE	(J) TRIATYPE	Mean Difference (I-J)	Std. Error	Sig.[a]	95% Confidence Interval for Difference[a] Lower Bound	Upper Bound
2D	Side	Top	.863	.727	.728	-.963	2.690
		Other	.012	.510	1.00	-1.270	1.294
	Top	Side	-.863	.727	.728	-2.690	.963
		Other	-.851	.673	.643	-2.544	.842
	Other	Side	-.012	.510	1.00	-1.294	1.270
		Top	.851	.673	.643	-.842	2.544
3D	Side	Top	3.686*	.727	.000	1.859	5.512
		Other	1.171	.510	.083	-.111	2.453
	Top	Side	-3.686*	.727	.000	-5.512	-1.859
		Other	-2.515*	.673	.002	-4.208	-.822
	Other	Side	-1.171	.510	.083	-2.453	.111
		Top	2.515*	.673	.002	.822	4.208
ExoVis	Side	Top	-.375	.727	1.00	-2.202	1.452
		Other	-.392	.510	1.00	-1.674	.890
	Top	Side	.375	.727	1.00	-1.452	2.202
		Other	-.017	.673	1.00	-1.710	1.676
	Other	Side	.392	.510	1.00	-.890	1.674
		Top	.017	.673	1.00	-1.676	1.710
OI	Side	Top	-.411	.727	1.00	-2.238	1.415
		Other	-.700	.510	.536	-1.982	.582
	Top	Side	.411	.727	1.00	-1.415	2.238
		Other	-.288	.673	1.00	-1.981	1.405
	Other	Side	.700	.510	.536	-.582	1.982
		Top	.288	.673	1.00	-1.405	1.981
In-place	Side	Top	.290	.727	1.00	-1.537	2.117
		Other	.600	.510	.741	-.682	1.882
	Top	Side	-.290	.727	1.00	-2.117	1.537
		Other	.310	.673	1.00	-1.383	2.003
	Other	Side	-.600	.510	.741	-1.882	.682
		Top	-.310	.673	1.00	-2.003	1.383

Based on estimated marginal means

*. The mean difference is significant at the .05 level.

a. Adjustment for multiple comparisons: Bonferroni.

4.2.4 Rating Scale Data

Test Statistics[a,b]

	Chi-Square	df	Asymp. Sig.
Difficulty	6.646	4	.156
Mental Effort	8.768	4	.067
Physical Effort	2.226	4	.694
Torus Orientation	3.293	4	.510
Plane Orientation	2.815	4	.589
Approximation	8.496	4	.075
Precision	3.306	4	.508
Likeability	3.207	4	.524

a. Kruskal Wallis Test

b. Grouping Variable: groupnum

5 Experiment 3: Qualitative Exploration

5.1 Rating Scale Data

Test Statistics[c]

	Z	Asymp. Sig. (2-tailed)
Easy to learn	-2.271[a]	.023
Clearly organized	-1.342[a]	.180
Easy to use	-2.070[b]	.038
Easy to complete the assigned task	-1.913[a]	.056
Easy to relate 2D and 3D views	-2.271[a]	.023
Easy to move the slices	-1.242[a]	.214
Easy to determine whether the anomaly was enclosed by the box	-.368[a]	.713
Easy to adjust the box size	-1.414[a]	.157

a. Based on negative ranks.

b. Based on positive ranks.

c. Wilcoxon Signed Ranks Test