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Cognitive Processes in Scientific Visualization

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ABSTRACT

What makes a graphic image a good visualization? Why is one visualization better than another? Why are 3D visualizations better than 2D visualizations in some cases but not others? How does the size of the display, color, contrast level, brightness or frame rate affect the usability of the visualization, and how do these "physical" quantities affect the type and amount of information that can be extracted from the visualization by the user? These are just a few of the questions that a multi-disciplinary effort at the Naval Research Laboratory are trying to answer. By combining visualization experts, physicists and cognitive scientists, we are trying to understand the cognitive processes carried out in the minds of scientists at the time they perform a visual analysis of their data. The results from this project are being used for the design of visualization methodologies and basic cognitive work. In this paper we present a general description of our project and a brief discussion of the results obtained trying to understand why 3D visualizations are sometimes better than 2D, as most of the attempts at studying this problem have resulted in theories that are either too vague or under-specified, or not informative across different contexts.

1. INTRODUCTION

Scientific Visualization is the process of displaying scientific data with computer graphics in a way that facilitates understanding and analysis. Recent advances in computer graphics software and hardware allow the creation of very compelling and colorful visualizations. Some visualizations even allow the user to be immersed within the visualization by using Virtual Reality technologies.[4] However the real effectiveness of these visualizations still remains to be evaluated (i.e., very little work has been done that evaluates the effectiveness of different visualizations, and how scientists actually use the visualizations).

What makes a graphic image a good visualization? Why is one visualization better than another? Why are 3D visualizations better than 2D visualizations in some cases but not others? How does the size of the display, color, contrast level, brightness or frame rate affect the usability of the visualization, and how do these "physical" quantities affect the type and amount of information that can be extracted from the visualization by the user?

These are just a few of the questions that a multi-disciplinary effort at the Naval Research Laboratory (NRL) are trying to answer. By combining visualization experts, physicists and cognitive scientists, we are trying to understand the cognitive processes carried out in the minds of scientists at the time they perform a visual analysis of their data. The results from this project are being used for the design of visualization methodologies and basic cognitive work. We expect these methodologies and research results to ease the labor of the scientist at the time they perform visualizations, which will then lead to better, quicker, and more robust scientific discovery.

Our ongoing research project tries to answer some of the questions posed in terms of the cognitions scientists are using. We are studying scientists working with their data using different visualizations.[12,14,15] We are also examining how these types of visualizations are used by non-experts. A big visualization effort at NRL is the use of Virtual Reality techniques to present scientific and technical information (Section 2). To evaluate this type of novel technology, we need to understand the advantage, if any, of 3D over 2D visualizations (Section 3). Most of the attempts at studying this problem have resulted in theories that are either too vague or under-specified, or not informative across different contexts. This paper reports our first effort to try to understand the importance of the

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visualization dimensionality by applying cognitive science. It has been proposed that a scientist's cognitive process starts by perceiving the visualization, and then performing "spatial transformations" on his mental representation of the visualization. By understanding these transformations, we will begin to understand why some visualizations are better than others (Section 4). We will present data from two different Navy applications: examining three dimensional micro-structures in binary steel alloys, and finding hot spots in a missile body impacted by an electromagnetic pulse (Section 5). The results are presented and analyzed in Section 6.

2. VIRTUAL REALITY SCIENTIFIC VISUALIZATION

In the next generation Navy, weapons systems - from material composition to functional requirement, will be designed and tested through large scale computational simulation and modeling, saving the DoD billions of dollars in live testing and laboratory processing. Such calculations are spanning length and time scales from the microscopic to the macroscopic so that continuum and first principle approaches must be co-calculated, resulting in massive, intricate scientific data sets that capture physical phenomena on both large and small scales. Little is known about the effective display of really complex scientific data sets, but scientific visualization of very large and highly complex data sets, has emerged as a critical part of the scientific process by exploiting the human brain's natural pattern recognition ability. Immersive virtual environments (VE) have been found valuable for visualizing these data sets, since such environments provide a natural human-computer interaction for data interrogation and analysis of 3D data sets.

The idea behind VR is to immerse human operators in a visually coupled teleoperated environment. By sensing the position and orientation of the operator's head with a sensor, and coupling the resulting data into a high performance computer graphics system, it is possible to generate a computer synthesized view of a virtual environment. This provides a natural control interface with the computer, as the system employs the three dimensional spatial processing capabilities of a human operator.

Real-time response and interactivity are very desirable characteristics for any VR scientific visualization device. The NRL's GROTTO (Graphical Room for Orientation, Training and Tactical Observation) is a CAVE^{TM}-like system that allows this degree of interactivity. GROTTO consists of three rear-projected screens (front and lateral walls) and one front projected screen (floor) occupying a 10 by 10 by 10 foot area. The projectors are driven by an SGI Onyx2 with IR graphics which can render millions of polygons per second. Stereoscopic vision is provided by using liquid crystal shutter glasses. The Onyx generates left and right eye images, and IR sensors, synched to the computer, operate in conjunction with the glasses to ensure the left eye images reach only the left eye and right eye images reach only the right eye. GROTTO is referred to as being an "immersive display" because its graphical display area covers the walls and floor of a room. Thus, instead of looking at the display, the user is immersed within the display. A half-dozen scientists can comfortably enter the GROTTO and jointly examine a scientific data set. Interaction with the GROTTO display occurs through a 3D wand (a type of 3D joystick) that is used primarily for navigation and object manipulation within the VE. Electromagnetic trackers are also employed to coordinate the scene view with the location of the viewer's head.

As part of our research, we are developing VR software for rapid prototyping of VR applications for scientific visualization.[3] Using this software, scientists develop visualization applications at their desktop and then port their application into the GROTTO without having to make a large investment in time and knowledge of computer graphics.

With this rapid prototyping environment, we were able to port more than 20 scientific applications to the GROTTO in a short period of time (less than one year). Applications were from ongoing NRL research projects, spanning diverse scientific areas: chemistry, material science, computational fluid dynamics, electrodynamics, solar physics and optics.

The scientists with whom we have been working with were not familiar with Virtual Environments (VE), their initial reaction ranged from skeptical to enthusiastic to the idea of porting their application to the GROTTO. After the port they all have shown great enthusiasm towards visualizing their data in a Virtual Environment, however, they still prefer to conduct their research at their desktops and regard the GROTTO as a multimodal presentation facility.

This rapid prototyping facility allows us to easily develop VR applications for any scientific/engineering researcher. With this low overhead of transitioning computational data to a VE, we were able to explore which applications worked best in the GROTTO.

3. 2D VS. 3D VISUALIZATIONS

One of our first goals is to understand why 3D visualizations are sometimes better than 2D. Previous experience at NRL demonstrates that in some cases, 3D is better than 2D for the analysis of data. In two cases, scientists were actually able to discover new information from going from 2D to 3D, and one scientist gained further insight by going from 3D to an immersive VR environment. While in both cases, the scientists were familiar with their data sets and 2D visualizations, they were not able to see the new highlights until they went to higher dimensionality displays.

Much of the research that has been performed comparing 2D and 3D visualizations is often confusing and contradictory. For example, for some tasks, 2D views or graphic representations are better than 3D views,[1,6,16] while for other tasks 3D views are better than 2D views.[2,7] Similarly, exocentric frames of reference are sometimes beneficial,[16] while other times egocentric frames of reference are better.[8] Most of these researchers explain their findings in terms of individual tasks that users perform rather than theoretical accounts: 3D representations are better than 2D representations for "object-oriented communicative situations in terms of appeal and the impression of depth"[7] or for "visualizing shapeless software information".[2] In addition, most of the attempts at reconciling/synthesizing this contradictory information have resulted in theories that are either too vague or under- specified (e.g., "make the representation compatible with the operator's mental model"[17]) or not informative across different contexts (e.g., 3D displays are better when integrating information[6]).

4. SPATIAL TRANSFORMATIONS

One way to reconcile this conflicting research is to assume that the more spatial transformations a user must perform in order to understand the view or solve the problem, the less useful that view is.[11] A spatial transformation is a mental operation the user performs on a view. A spatial transformation can be mental rotations,[9,12] time series progression prediction, object or data movement, transforming a view on a 2D screen to a 3D mental image, or anything else the user mentally does to the data in order to understand it or facilitate problem solving. Trafton suggests that the more spatial transformations a user must mentally perform, the more difficult a view is to understand and use. Trafton goes on to suggest that spatial transformations occur at two different times: problem representation and understanding, and during problem solving. If the number of spatial transformations a user must do to a view does influence the usefulness of a view, then the implications for scientific visualization are clear: build a system that presents views that scientists initially understand and in a form they expect to see, and then provide scientists ways of viewing their data so they do not need to do as many spatial transformations.

The overall objective of this project is to examine the hypothesis that the more spatial transformations a user must perform, the less useful a view is, and investigate which types of spatial transformations are more difficult or time consuming than others. In addition to the basic research questions, the results of this research will allow much better scientific visualization tools to be created. Specifically, the new tools that will be created will provide views that scientists expect to see and provide ways of transforming the data set via hardware/software, rather than mentally. This new set of tools will greatly simplify the scientists' visualization job.

If the above hypothesis is correct, then, it is clear that views presented to scientists must be the ones that need fewer spatial transformations to be understood. Almost all of the visualization tools that scientists currently use present the views on a 2D screen. Because many of the tasks that scientists need to accomplish require examining data in three or more dimensions, a 2D screen increases the number of spatial transformations, often making the task more difficult compared to a stereoscopic 3D environment like the GROTTO. Of course, some of the data sets that scientists visualize using a 2D screen do not need many spatial transformations, so in those cases a 3D environment is not needed. Determining the number of spatial transformations a scientist needs to do at certain kinds of tasks is a key question in this research.

5. CASE STUDIES

For our first experiment we concentrated on two visualizations that scientists have been using the GROTTO for demonstrations and presentations. In both cases, scientists initially performed a 2D visualization, and then they moved to a 3D rendition of their data sets. Also, both research groups are avid supporters of GROTTO visualizations.

What we will try to understand in this study is if stereoscopic 3D visualization is good for both projects, or at least superior to 2D visualizations. Let us briefly describe each of the projects and the relevance of the visualization to the understanding of the physical phenomena involved in each case.

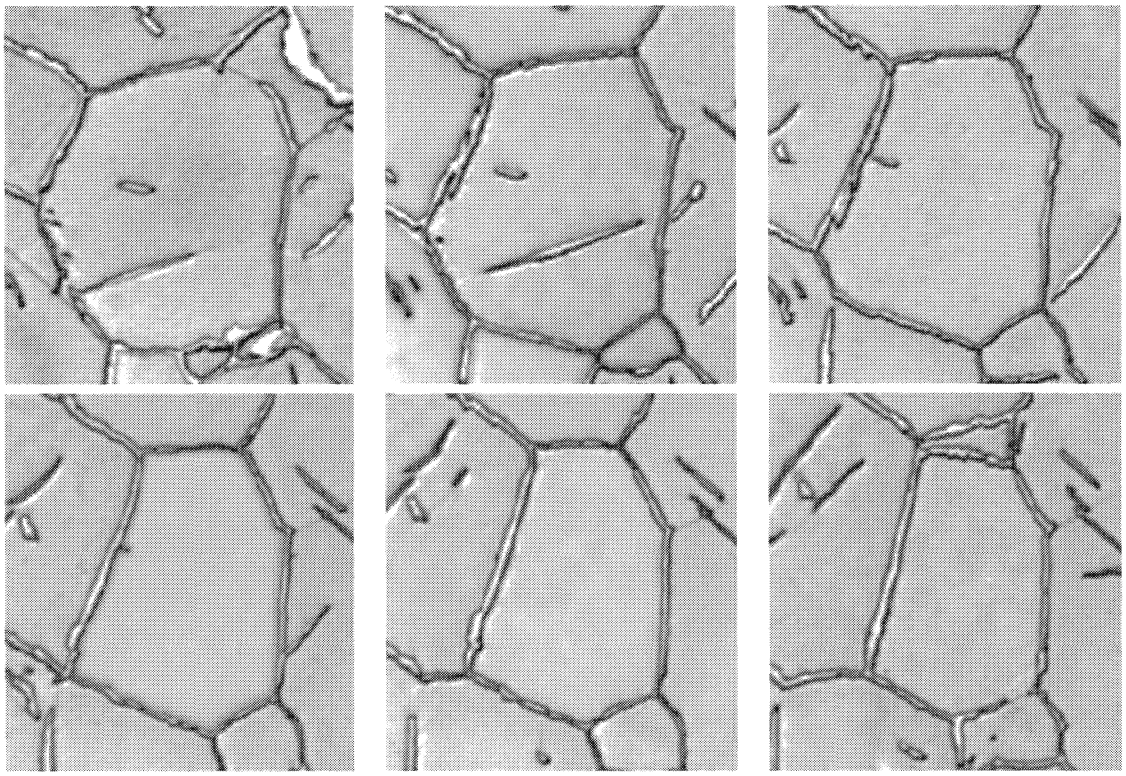

Figure 1. 2D Visualization of a Microstructure.

5.1. Microstructures

The influence of the internal microscopic structures of materials, i.e., microstructures, on the mechanical properties of materials is well established. To fully understand the interaction between structure and properties, it is critical that materials scientists comprehend the 3D shape of the microstructures. This example involves a technique for the 3D analysis of microstructures of materials.[5] The technique consists of incrementally polishing through a thin layer (approximately 0.2 μm) of material, chemically etching the polished surface, applying reference marks, and performing optical or scanning electron microscopy on selected areas. The series of images are then processed, employing AVS and other visualization software, to obtain a 3D reconstruction of the material.

The traditional 2D visualization is performed by viewing the sequence of images parallel to the sectioning direction. In Figure 1 we show a series of images through the material, every tenth section ($\sim 2\mu m$) is shown. These traditional methods suffer from a serious drawback: even simple three-dimensional shapes often cannot be deduced from examining random planes of polish, much less the complex morphologies and distributions of grains found in many materials. Only in recent years have serial sectioning techniques been enhanced by computer visualization to obtain more useful 3D information.

The 3D reconstruction is done by digitally modifying each image to improve the contrast. Next, the image stack from all the sections is converted into a volume data set (a 3D scalar field) and an isosurface is generated. This isosurface represents the 3D reconstruction of the microstructure. In particular, we applied this technique to a sample of alloy steel using a stack of 250 images. The 3D reconstruction showed microstructural features not previously identified with traditional 2D techniques on single planes of polish.

The GROTTO allowed the inspection of the microstructures both as a whole and then the separation and study of the individual components (Figure 2). The three dimensional effect produced and the size of the images displayed were enough to give the user a real sense of the morphology of the microstructures and their spatial distribution that cannot be matched by the normal computer monitor screen. During one of the GROTTO sessions an important discovery was made by the principal scientist (George Spanos); a new kind of structure was observed that had not

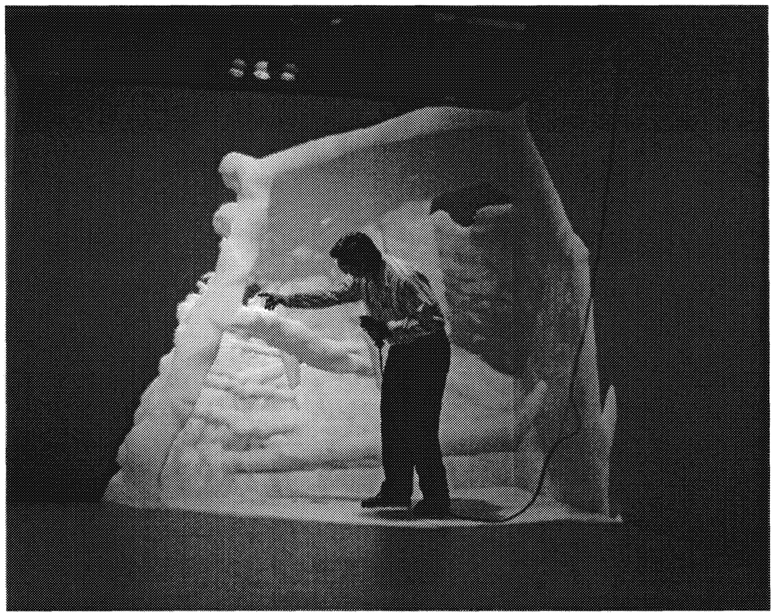

Figure 2. 3D Visualization of a Microstructure in the GROTTO.

seen before. While such structure can be observed in the computer monitor screen, it had not been noticed until the examination in the GROTTO. This shows that the capabilities of the GROTTO may actually ease the labor of the scientist, at least in the analysis of three dimensional information. We also feel the GROTTO shows great potential as a device for the communication and dissemination of this type of visual information.

In this example, scientists are interested in the three dimensional morphology of the internal microscopic structures of materials. Of particular importance is the number and shape of precipitates inside the microstructure. A precipitate is one of the objects that resemble stalactites in Figure 2.

It is important to note, that in this case, the two important things of the data set are geometrical features. So, it is clear that the cognitive abilities of the scientist will be improved if we can show them these geometric properties in such a way that they do not have to perform several mental space transformations.

5.2. Electromagnetic Pulse Propagation

In this example, scientist simulate the effect of high-power microwave interactions with a missile body.[10] These interactions have potentially important consequences on the electronics components of the missile, such as steering and navigation, and could be used by anti-missile defense systems. Because these interactions take place while the missile body is traveling at extreme altitudes and speeds, they are very difficult to study experimentally.

To generalize missile bodies, scientists have used various cylindrical cavities. One widely recognized standard cylindrical model is the so-called NATO cylinder. This is a closed metal cylinder of inside length 50 cm, diameter 25 cm and wall thickness 1 cm, and having a central entrance hole at one end of diameter 10 cm. In addition, there are three slots in the side wall, two parallel to the cylinder axis and one azimuthally oriented, midway along the cylinder, which break the 2D symmetry of the cavity. In addition, in actual testing a thin field strength probe is inserted at various distances into the cylinder along the center axis to make measurements of the field. This idealized cavity has been used in numerous experimental and computational studies to test how well EM codes can reproduce the fields in targets of interest to NATO.

The simulation shows an electromagnetic pulse propagating and impacting one side of the NATO standard cylinder. As time progresses, the pulse propagates inside the cylinder and produces "hot spots". A hot spot is a zone of local maximum electromagnetic energy density. Scientist are interested in the localization of the hot spots, as this means that when they design a satellite, they move the sensitive electronic components away from a hot spot.

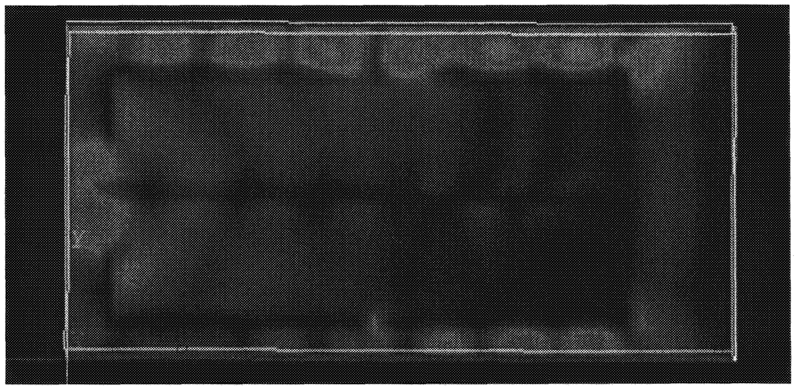

Figure 3. 2D Visualization of the EMP.

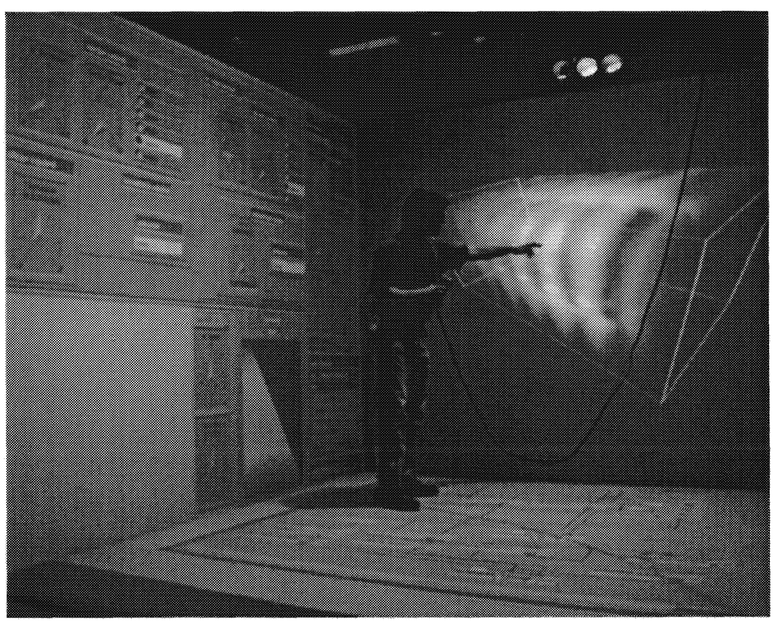

Figure 4. 3D Visualization of the EMP in the GROTTO.

Table 1. Initial Results by Respondent (w = wrong, r = right).

Group.Individual	MS Comments Wrong	MS Comments Right	MS # of Precipitates	MS # of Unique Shapes	EMP Comments Wrong	EMP Comments Right	EMP # of Hot Spots
1.1	1	0	w	w	1	0	r
1.2	0	2	r	r	0	2	r
1.3	2	0	w	w	1	0	w
1.4	2	3	w	w	4	1	r
1.5	3	1	r	w	2	1	r
2.1	0	3	r	r	0	0	r
2.2	0	3	r	w	2	1	r
2.3	0	2	r	r	1	1	w
2.4	0	1	r	r	0	3	w
2.5	3	1	r	w	2	1	r
2.6	1	2	r	r	0	2	r

Figure 3 shows the 2D visualization of the data set. A cross section has been taken from the cylinder and the electromagnetic energy density is shown on this plane. Figure 4 shows the volume visualization of the electromagnetic energy density of the same data set.

So, cognitive abilities in the scientist will be enhanced if we can show them the localization of the hot spots, without them having to perform extensive space transformations.

6. INITIAL RESULTS

Our initial experiment consisted of 10 non-experts subjects and one domain expert subject. They were divided in two groups, Group 1 and Group 2, and each group was shown different visualizations in 2D and 3D. The Group 1 was shown the material sciences (MS) example in 2D followed by the electromagnetic pulse (EMP) propagation in 3D. Group 2 was shown the material science example in 3D followed by the EMP propagation in 2D.

After a brief explanation of each case, the visualization was shown. During this time, the subjects were required to answer some questions. For the case of the Material Science visualization, they were asked to write down any important features they were observing, and to answer how many precipitates and how many types of precipitates were present. For the EMP visualization they were asked to write down any important features they were observing, and the number of hot spots in the cylinder.

The results are shown in Table 1. The first column designates which group the individual was from, group 1 or 2. Columns two through five refer to viewing the MS visualization and columns six through eight refer to the EMP visualization. Columns two and three and six and seven indicate the number of wrong(w) and right(r) comments that were found in the respondent's survey. Columns four, five and eight indicate whether or not the respondents got the quantitative questions correct.

These results suggest that the participants who saw the Material Science 3D visualization were more accurate than the participants who saw the 2D Material Science visualization (82% vs. 37%) *. The participants who saw the EMP 3D visualization, however, were not more accurate than those participants who saw the 2D visualization (31% vs. 63%)†. In other words, the 3D visualization was better for the Material Science case, while there was no statistical difference between 2D and 3D for the EMP example. It is important to note that these problems were very hard: the domain expert was the only participant to get everything right.

The meaning of these results is clear for the case of the Material Science experiment. The 2D visualization shows slices of the data set. In order to count the number of precipitates, the user has to "interpolate" and reconstruct

*By applying statistical methods commonly used in cognitive science, we can determine that 82% of the participants were more accurate while viewing the data in 3D, while only 37% of them were more accurate while viewing the data in 2D. A *t-test* and probability values of $t(5) = 2.8$ and $p < .05$ suggest that the result is not due to a random variation

†In a similar way, we obtain $t(5) = 1.9, p > .10$ which suggests that there is no statistical difference between the two visualizations for the EMP data set.

the 3D shape of the microstructure in 3D. The 3D visualization provides the user with the reconstructed image, and they need only count precipitates. In other words, the 3D visualization has fewer spatial transformations than the 2D visualization. Because the 3D has fewer spatial transformations, it is the better visualization.[11]

For the EMP case, the situation is more difficult to understand. We first thought that the 2D image was brighter than the 3D image and that in 2D there is no occlusion of hot spots by extraneous parts of the volume, so the counting task is easier. We returned to the GROTTO to view the 2D and 3D visualizations and it became clear that the images were different. We had used a slightly different color table for the 2D image than the 3D image and so the number of hot-spots could be counted differently for the two images. It was thought that this difference was more crucial than image brightness or volume occlusion. However, it can be seen that the number of right (wrong) comments is significantly higher (lower) for the 2D case. A possible interpretation is that the subjects viewing the 3D visualization had to perform extra mental rotations (to align the cylinder) and interpolations (to count for occlusion effects), making more difficult the cognitive process.

7. CONCLUSIONS

Scientific visualization is becoming an important part of the scientific process. New visualization techniques are needed to display in a clear way the vast amount of data produced by modern supercomputers. Computer graphics techniques have allowed very awesome visualization systems. One of the most impressive ways to display scientific information is by using Virtual Reality.

But how good are these visualizations? How good is the GROTTO to help scientist to understand their data?. There is currently no practical way to evaluate visualizations. We propose that the best way to tell when a visualization is good is when it helps the user to acquire new information (information relevant to the subject matter). In other words, a good visualization is when it can enhance the cognitive abilities of the user by reducing the number of spatial transformations.

The concept of the number of mental spatial transformations needed to be performed to extract new information of the visualization is important to understand the cognitive process. And can provide a metric on the quality of the visualizations.

Collaboration between cognition scientists and visualization experts is necessary to improve the design of visualization tools. By understanding the cognitive process carried out by scientist looking at the visualization of their data, we expect to be able to improve the design of current visualizations, and to tell when a novel and expensive technology such as an immersive room is likely to improve the research work.

The advantage or disadvantage of 3D visualizations in comparison to their 2D counterparts has been a polemic for many years now. While it has not established a definite answer, we think that cognitive science can shed some light to this problem. We showed that in one case 3D is better than 2D, but not on the basis of the use of perception issues, but in cognition terms. We hope to fine tune our visualizations so that future experiments will clearly resolve these issues.

8. ACKNOWLEDGEMENTS

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