ASSESSMENT CRITERIA FOR COMPREHENSIBILITY IN VISUALIZATION ENVIRONMENTS

YOJANA JOSHI

A THESIS

IN

THE DEPARTMENT

OF

COMPUTER SCIENCE AND SOFTWARE ENGINEERING

PRESENTED IN PARTIAL FULFILLMENT OF THE REQUIREMENTS
FOR THE DEGREE OF MASTER OF COMPUTER SCIENCE AT
CONCORDIA UNIVERSITY
MONTREAL, QUEBEC, CANADA

NOVEMBER 2005

Your file Votre référence
ISBN: 0-494-14322-3
Our file Notre référence
ISBN: 0-494-14322-3

ABSTRACT

ASSESSMENT CRITERIA FOR COMPREHENSIBILITY IN VISUALIZATION ENVIRONMENTS

Yojana Joshi

Visualization is essentially a cognitive process in which humans form a mental model or image in their minds to enable them to comprehend complex information about the artifacts, relationships, process, phenomena, etc. under study. Computer based visualization environments combine interactivity with visual renderings of the data in the form of suitable tools and techniques to support this comprehension process. In spite of the plethora of visualization tools and techniques that have evolved, visualization environments are often not very effective in their support of this comprehension process. Clearly we need quantitative measures to asses the effectiveness of a visualization environment. Given the cognitive nature of visualization the two main questions are – what do we asses and how? In this research, we have adopted a systematic approach towards providing answers to these questions. We identify that there could exist a gap between the information "communication" intent of the visualization environment and the information "seeking" intent of the user. Our premise is that smaller this gap more effective is the visualization environment in terms of information comprehended by the user. We also believe that it is important to characterize this "gap" in terms of quantifiable parameters. Towards this goal, we have first reviewed the related work done in this field. This review has led us to do an in-depth study of psychological and visual communication aspects of a visualization environment. As a result of this study and other usability experiments conducted by us, our main thesis from this research is that this "gap" can be characterized by a set of criteria which would enable us to assess visualization environments for such effectiveness. The basis for these "comprehensibility criteria" is provided by Norman's Theory of Human Action Cycle which describes how humans tend to interact with the outside world and Visual Communication principles by Aaron Marcus which describe the principles that should be followed so that graphical user interfaces can communicate effectively with its users. A substantial part of our

research was devoted to conducting usability experiments with two different visualization environments as case studies towards providing empirical validation of these criteria. We describe these usability experiments and present empirical validation results obtained; basically by observing the user's physical actions to the visualization environment's responses and by assessing the "visual representation" itself.

To the loving memory of my dear father

ACKNOWLEDGEMENTS

I wish to express my sincere appreciation and gratitude to my supervisors Dr. Sudhir Mudur and Dr. Ahmed Seffah.

The whole thesis would have been impossible without Dr. Mudur's support and guidance. He has been and will always remain a source of inspiration for me in whatever task I undertake. I am extremely grateful to Dr. Seffah for his continuous encouragement and guidance throughout my research work. I want to thank him for giving me excellent opportunities to participate in a number of challenging and interesting projects as a member of the HCSE (Human Software Engineering) Group at Concordia University.

I am grateful to Dr. Rachid Gherbi and Ms. Charlotte Davies for giving me the opportunity to study their visualization environment for my research.

I also take this opportunity to thank all the team members of HCSE Group for being such a great team to work with on various group projects. My special thanks go to Mr. Qing Li, Ms. Naouel Moha for being my good friends at Concordia University.

Finally, this thesis wouldn't have been possible without the strongest support from my family. I am extremely thankful to my parents for their constant encouragement and guidance. Last but not the least, I would like to thank my fiancé Anand for always believing in me and giving me all the strength I needed to complete the thesis.

TABLE OF CONTENTS

TABLE OF FIGURES xii
TABLE OF TABLES xiv
Chapter 1: INTRODUCTION 1
1.1 Visualization Environment 2
1.2 Applications Domains of Visualization Environments 3
1.2.1 Data Type-based Classification 4
1.2.2 Cognitive Classification 6
1.3 User Interaction in Visualization Environments 6
1.3.1 Interaction Styles 7
1.3.1 Interaction Devices 7
1.4 Validation 8
1.5 Thesis Organization 9
Chapter 2: LITERATURE REVIEW 11
2.1 Assessment Methods for Visualization Environments 13
2.2 Assessment Metrics for Visualization Environments 15
2.3 Perceptual and Cognitive Factors for Visualization Environments 16
2.4 Discussion 20
Chapter 3: COMPREHENSION GAP CHARACTERIZATION 21
3.1 Understanding the Comprehension Gap between the Visualization Environment and User 21
3.1.1 Norman's Seven-Stages Action Cycle 22
3.1.2 Donald Norman's Gulf of Execution and Evaluation: 23
3.2 Understanding Human Information Processing Capabilities 25
3.2.1 Review of Human Information Processing Models 25
3.2.2 Selection of "Model Human Processor" 27
3.2.3 Perception Theories 29
3.2.3.1 Constructivist Theory of Perception 29
3.2.3.3 Ecological Approach in Perception 29
3.2.4 Mapping of "Model Human Processor" 30

3.3 Understanding Visualization Environment 30
3.3.1 Review of Visualization Environment Models 31
3.3.2 Choice of Model for Visualization Environment 32
3.3.3 Mapping of "SIGGRAPH Model for Visualization Environment" 33
3.3.4 Norman's Action Cycle Revisited 34
3.4 Communication between Visualization Environment and User 35
3.4.1 Communication Process 35
3.4.2 Application of Visual Communication Principles 35
3.4.3 Application of Cognitive Principles 36
3.5 Summary 37
Chapter 4: COMPREHENSIBILITY CRITERIA FOR VISUALIZATION ENVIRONMENTS 38
4.1 Use of word "Comprehensibility Criteria" 38
4.2 Organize 39
4.2.1 Consistency 40
4.2.2 Navigability 40
4.2.3 Clustering 41
4.2.4 Affordance 42
4.2.5 Constraints 43
4.2.6 Dynamism 44
4.2.7 Depth Perception 45
4.2.8 Collection of "Organize" criteria 46
4.3 Economize 47
4.3.1 Simplicity 47
4.3.2 Clarity / Intuitiveness 47
4.3.3 Distinctiveness 48
4.3.4 Emphasis 49
4.3.5 Collection of "Economize" criteria 50
4.4 Communicate 50
4.4.1 Legibility 51
4.4.2 Readability 51

4.4.3 Symbolism 53
4.4.4 Multiple views 53
4.4.5 Effect of Color 54
4.4.6 Mapping 55
4.4.7 Responsiveness 56
4.4.8 Contextualization 57
4.4.9 Collection of "Economize" criteria 58
4.5 Collective Set of Criteria for Visualization Environments 59
4.6 Experimental Validation 61
Chapter 5: CASE STUDY I - OSMOSE 62
5.1 Immersive Visualization Environment: OSMOSE 62
5.2 Artist's Description of OSMOSE 63
5.3 Using OSMOSE 63
5.4 Comprehensibility Study of OSMOSE 64
5.4.1 Goal 64
5.4.2 Objectives 64
5.4.3 Constraints in the study 64
5.4.4 Tasks 64
5.4.5 Participants 65
5.4.6 Usability Testing Process 65
5.5 Understanding visual communication between OSMOSE and participant's "Model Human processor" 65
5.6 Summary of Observations and User Comments 67
5.6.1 Consistency 67
5.6.2 Navigability 68
5.6.3 Clustering 68
5.6.4 Affordance 68
5.6.5 Constraints 69
5.6.6 Dynamism 70
5.6.7 Distinctiveness 70
5.6.8 Emphasis 70

5.6.9 Legibility 70
5.6.10 Readability 71
5.6.11 Symbolism 71
5.6.11 Effect of color 72
5.6.12 Mapping 72
5.6.13 Responsiveness 73
5.6.14 New Criterion from Observations and User Comments 73
5.7 Descriptive Statistics of Participants Responses to Post Test Questionnaire 74
5.7.1 Effect of affordances on presence 74
5.7.2 Effect of mapping on user interaction 75
5.7.3 Effect of navigability on user interaction 77
5.7.4 Effect of physical constraints on presence 77
5.7.5 Effect of responsiveness on user interaction 78
5.7.6 Effect of readability on user comprehension 79
5.8 Concluding Remarks 82
Chapter 6: CASE STUDY II – ADN VIEWER 83
6.1 DNA Visualization Environment: ADN-Viewer 83
6.2 Developer's description about ADN-Viewer 83
6.3 Using ADN-Viewer 84
6.4 Comprehensibility Study of ADN-Viewer 84
6.4.1 Goal 84
6.4.2 Constraints 85
6.4.3 Usability testing process 85
6.4.4 Tasks 85
6.4.5 Participants 86
6.5 Understanding Visual Communication between ADN-Viewer and "Model Human Processor" 89
6.6 Summary of Observations 90
6.6.1 Observations about Clustering 90
6.6.2 Desire for Affordances 91
6.6.3 Use of conventions as positive transfer effect 91

6.6.4 Distinctiveness and emphasis due to effect of colors 91
6.6.5 Symbolism 92
6.7 Descriptive statistics of participants' responses to questionnaires 92
6.7.1 Responses about Real world consistency 93
6.7.2 Navigability in ADN-Viewer 93
6.7.3 Dynamism in ADN-Viewer 94
6.7.4 Responses on effect of Depth Perception 95
6.7.5 Responses on Directionality 96
6.7.6 Responses on Simplicity 97
6.7.7 Intuitiveness in ADN-Viewer 98
6.7.8 Legibility in ADN-Viewer 99
6.7.9 Readability in ADN-Viewer 101
6.7.10 Effect of multiple views in ADN-Viewer 102
6.7.11 Effect of colors in ADN-Viewer 103
6.7.12 Mappings in ADN-Viewer 104
6.7.13 Responsiveness of ADN-Viewer 105
6.7.14 Effect of Contextualization on participants 106
6.8 Concluding Remarks 107
Chapter 7: CONCLUSIONS AND FUTURE WORK 110
7.1 Summary of Contributions 110
7.2 Conclusions 111
7.2.1 Norman's Gulf of execution and evaluations: 111
7.2.2 Validation of Criteria 112
7.3 Future Work 113
References 115
Appendix A - Details of "Comprehensibility Study of OSMOSE" 121
Appendix B - Details of "Comprehensibility Study of ADN-Viewer" 145

TABLE OF FIGURES

Fig. 3. 1 Two Aspects of Human Action 22
Fig. 3. 2 Norman's Seven-Stages Action Cycle 23
Fig. 3. 3 Model for Comprehension Gap Between Visualization Environment and User 24
Fig. 3. 4 Human Information Processing Stages by (Lindsay & Norman 1977) 25
Fig. 3. 5 Extended Human Information Processing Model by (Barber 1988) 26
Fig. 3. 6 Multi Store Memory Model by (Atkinson & Shiffrin 1968) 26
Fig. 3. 7 Model Human Processor by (Card, Moran & Newell 1983) 28
Fig. 3. 8 Mapping of "Model Human Processor" on "Model for Comprehension Gap".. 30
Fig. 3. 9 Visualization Model by (Robertson & De Ferrari 1994) 31
Fig. 3. 10 SIGGRAPH Model for User and User Interface Modules of a Visualization System 32
Fig. 3. 11 Mapping of "SIGGRAPH model of Visualization Environment" on "Model for Comprehension Gap" 33
Fig. 3. 12 Norman's Seven-Stage Action Cycle Revisited 34

Fig. 4. 1 Set of Criteria under "Organize" principle 46
Fig. 4. 2 Set of Criteria under "Economize" principle 50
Fig. 4. 3 Set of Criteria under "Communicate" principle 58
Fig. 4. 4 Proposed Set of Assessment Criteria for Comprehensibility in Visualization Environments 59

Fig. 5. 1 Head Mounted Display used in OSMOSE 63
Fig. 5. 2 Visual Communication between OSMOSE and user 66
Fig. 5. 3 Effect of Affordances on Presence 75
Fig. 5. 4 Effect of mappings on user interaction 76
Fig. 5. 5 Rating for navigation actions for OSMOSE 77
Fig. 5. 6 Effect of Physical Constraints on Presence 78
Fig. 5. 7 Effect of Responsiveness on User Interaction 78
Fig. 5. 8 Results about Invitingness and Attractiveness of OSMOSE 79
Fig. 5. 9 Results about Understanding OSMOSE 80

Fig. 5. 10 Results about objects and colors seen in OSMOSE 80
Fig. 5. 11 Attention towards a particular object.......... 141
Fig. 5. 12 Reason behind liking OSMOSE.......... 142
Fig. 5. 13 Results about remembering objects in OSMOSE.......... 143
Fig. 5. 14 Results about remembering colors in OSMOSE 144

Fig. 6. 1 Scores for ADN-Viewer Participants 88
Fig. 6. 2 Visual Communication Between ADN-Viewer and User.......... 90
Fig. 6. 3 Responses about Real World Consistency 93
Fig. 6. 4 Responses about Navigation Actions in ADN-Viewer 94
Fig. 6. 5 Responses about Dynamism in ADN-Viewer.......... 95
Fig. 6. 6 Depth Perception in ADN-Viewer 96
Fig. 6. 7 Importance and Sufficiency of Directionality in ADN-Viewer 97
Fig. 6. 8 Simplicity in ADN-Viewer.......... 98
Fig. 6. 9 Intuitive Tasks in ADN-Viewer 98
Fig. 6. 10 Responses about Legibility in ADN-Viewer.......... 99
Fig. 6. 11 Evidence of Legibility Problem in ADN-Viewer.......... 100
Fig. 6. 12 User Ratings for Sequence Grouping Task 101
Fig. 6. 13 User Performance for Sequence Analysis Task 102
Fig. 6. 14 Reponses about Multiple Views in ADN-Viewer 103
Fig. 6. 15 Responses about Colors in ADN-Viewer.......... 104
Fig. 6. 16 Mappings Suggested by Participants for ADN-Viewer Navigation.......... 105
Fig. 6. 17 Responsiveness of ADN-Viewer.......... 106
Fig. 6. 18 Importance of Contextualization in ADN-Viewer 106
Fig. 6. 19 Comfort Level in Exploring the Context in ADN-Viewer.......... 107
Fig. 6. 20 Comparison of the ADN-Viewer Performance with and without glasses...... 169

TABLE OF TABLES

Table 4. 1 Mapping of Aaron Marcus and Donald Norman principles onto one collective set 60

Table 6. 1 Scoring Scheme for User Evaluation Questions 87

Table 7. 1 Validation Covered for Comprehensibility criteria in Two Case Studies 112

Chapter 1: INTRODUCTION

With information technology pervading virtually all aspects of our life, and the resultant need to analyze large amounts of multivariate data, many areas in science, arts, commerce and technology depend on exploratory data analysis and visualization. The primary purpose of any visualization is to communicate information using the visual medium, i.e. to portray a set of data in a pictorial form that facilitates easy comprehension of complex and possibly deeply embedded information. With tremendous progress in interactive graphics technology, visualization is no longer restricted to single static pictorial representations. Rather, it could consist of dynamically changing views of the data as desired and specified by the user through the interaction mechanisms supported in the environment. Hence it is the overall visualization environment that supports this comprehension process. Over the last four decades, many different computer based visualization environments have evolved supporting different tools and techniques. It is a well established fact that no single environment is effective in all domains. In fact, it is often lamented that many systems produce flashy pictures but are ineffective. Clearly there is a need to systematically assess the effectiveness of a visualization environment. There are however the two main questions – what should one assess and how? In this research, we have explored a systematic approach for the assessment of interactive visualization environments for their effectiveness in this information comprehension process of the user. We identify that there could exist a gap between the information "communication" intent of the visualization environment and the information "seeking" intent of the user. Our premise is that smaller this gap more effective is the visualization environment in terms of information comprehended by the user. Our goal is to characterize this "gap" in terms of quantifiable parameters. For this, we have first reviewed the related work done in this field. This review has led us to do an in-depth study of psychological and visual communication aspects of a visualization environment. As a result of this study and other usability experiments conducted by us, our main thesis from this research is that this "gap" can be characterized by a set of criteria which thus enable us to assess visualization environments for such effectiveness. A substantial part of our research was devoted to conducting usability experiments with two different visualization environments as case studies towards providing empirical validation of these criteria. The first is an immersive 3D art environment while the second is interactive 3D scientific visualization software. We describe these usability experiments and present empirical validation results obtained; basically by observing the user's physical actions to the visualization environment's responses and by assessing the "visual representation" itself.

This chapter briefly introduces the importance of visualization, application domains of visualization environments, significance of user interaction, problems encountered in assessing visualization environments for their effectiveness in information comprehension by the user and finally organization of the rest of this thesis.

1.1 Visualization Environment

Visualisation can be defined as the visual representation of data. It is important in understanding of information embedded in the data and in gaining knowledge about the artefacts, relationships, processes, phenomena, etc. under study. Why? An answer to this can be found in following definitions from the dictionaries.

"Visualization" (noun) is the power or process of forming a mental picture or vision of something not actually present to the sight. (Oxford English Dictionary 2005)

"To visualize" (verb) is to form a mental vision, image, or picture of (something not visible or present to the sight, or of an abstraction); to make visible to the mind or imagination. (Oxford English Dictionary 2005)

From these definitions, we realize that visualization is an activity which a human being engages in, in other words, it goes on in the mind of the viewer (user). (Spence 2001) We can see the cognitive nature of this process and this is what makes the goal of assessing visualization environments so difficult.

So far, we should note that these definitions do not mention "computer" though, in this research our focus is on the, study of computer based "visualization environments" which facilitate in this cognitive process of visualization. One more definition of "visualization" does seem to accommodate this aspect.

"Visualization" (noun) is the action or process of rendering visible.(Oxford English Dictionary 2005)

In this definition, the action or process of rendering the visible representation of data could be carried out by a computer on a surface (say, computer screen), on initiation by the viewer. We shall use the term "visualization environment" because we wish to refer to the overall physical and logical structure, or particular combination of hardware, software and interface through which a user views and interacts with the "visual representation". (*Oxford English Dictionary* 2005)

1.2 Applications Domains of Visualization Environments

Application domains for visualization environments range from bioinformatics to military training and from business to software engineering (Hansen & Johnson 2005). In the emerging field of bioinformatics, direct visualization of biological material tells us much about the structure and mode of action of macromolecules. Protein molecules can be studied for the visual analysis of these macromolecular structures. In military training programs, flight simulators are used which simulate the real world scenario on the large screen and train pilots for the challenging situations which they might face in the real world. In medicine, scientific visualization can help doctors and surgeons to see the graphical representations of the patient's scans so that they can take more informed decisions on the line of treatment to follow. Business data visualization environments visualize large amount of abstract data to show the patterns and trends in certain data variables so that the company managers and stakeholders are well informed about their company's performance. Software visualization environments help the entire software development team from software developers to project leaders to visualize abstract software architectures in the form of "program code landscapes" or component and network diagrams of the software, etc. In education, visualization environments are used in teaching subjects like physics, biology, geography and geology, where students can see the visual simulations of the concepts and phenomena they are learning.

Depending on these different application domains, visualization environments get different names such as "scientific visualization", "business data visualization", "medical visualization" or "software visualization" etc. The purpose in using visualization environments in each of these domains could be for planning, strategic decision making, exploring, testing, and learning or training tasks.

Apart from this generalized domain-based classification, we briefly discuss below two specific taxonomies of visualization environments that are described in the literature.

1.2.1 Data Type-based Classification

On-line Library of Information Visualization Environments (OLIVE) by computer science students of University of Maryland, at College Park, categorizes "information visualization environments" into eight categories based on the type of data involved. (*On-line Library of Information Visualization Environments* 1997) The categories are temporal, 1D, 2D, 3D, multi-D, tree, network, and workspace where D stands for "Dimension". Some of the main categories are explained below with examples:

- Animations, project timelines, video representations are examples of temporal data visualization where data is modified over time.
- One dimensional (1D) data visualizations are in the form of search results or sequential lists where visual perception attributes such as color are used to represent the relative importance of certain data elements.
- Two representative examples for two-dimensional (2D) visualizations are newspaper layouts and geographic information systems. Distance, location, direction and size are the attributes that can be effectively illustrated using a 2D visualization environment.
- Three-dimensional (3D) visualizations are used for three dimensional objects and scenes. According to OLIVE, surface and volume visualization are the most widely

used techniques where real world 3D objects or scanned 3D datasets are rendered in the form of computerized representations and projected on 2D screen. This type of visualization provides the opportunity to understand the inner or unexplored parts of the objects that the 3D datasets represent. Another advantage of using 3D visualization is the ability to do a virtual walkthrough of the 3D representations of the dataset to understand spatial relationships better.

- Stock market statistics or company's performance data are examples of abstract and statistical information about a phenomenon where all the attributes have approximately equal weights.

Even though the above discussion has focussed on different types of visualization environments based on the type of data being studied, there is one aspect which brings real power to all these types of visualization environments: interactivity. The additional strength is in the interaction that its users are provided with to manipulate different attributes and to see the visual rendered in different ways. For example, let us consider some of the categories in OLIVE:

- In temporal data, users can manipulate time and change the temporal order of the information being viewed, so that they can find new patterns and/or visions.
- In 1D visualization environments, users can filter the unwanted data items from the dataset, or traverse and find the important data elements.
- In 2D datasets, zooming on a specific part of the visualization, designing layouts or traversing the visual are the typical tasks that users carry out.
- For 3D datasets, visualization environments provide the power to explore the inner parts of three dimensional computerized objects in volume visualization or to navigate through a computer-generated 3D space. This makes the dynamic methods of a 3D visualization environment distinctively different from the traditional ways of looking at static visual images of datasets.

1.2.2 Cognitive Classification

In (Wiss & Carr 1998), a cognitive classification framework has been proposed to classify three dimensional information visualizations. It is based on three cognitive aspects: attention, abstraction and affordances. Here, the authors explain that they are important aspects for classifying visualization environments because the purpose of information visualization is to communicate information to humans. They study fifteen visualization designs considering these classification criteria and present their findings in which they say that affordances are scarcely present while attention and abstraction factors are well taken care of in the visualization environments. Hence, they suggest that we should consider three-dimensional information visualization environments as providing a full-fledged user interface than just three-dimensional graphics. We see this as one of the few attempts to study the cognitive nature of "visualization" and to use the cognitive nature to classify a specific subset, namely 3D visualization environments.

1.3 User Interaction in Visualization Environments

According to the dictionary meaning, being interactive means:

"Being a computer or other electronic device that allows a two-way flow of information between it and a user, responding immediately to the latter's input."(Oxford English Dictionary 2005)

The ability to explore the visual representation interactively is so valuable that a great deal of effort has been invested in the invention and implementation of interactive visualization environments that utilize this potential (Spence 2001). If we consider HCI as a whole, human-computer interaction is a discipline concerned with the design, evaluation and interactions of interactive computing systems (Hewett et al. 2004). Below, we present an overview of such human computer interaction styles, and some important interaction devices used in interactive visualization environments.

1.3.1 Interaction Styles

The conventional approach for any visualization environment is to provide a GUI (Graphical user interface) which "surrounds" the "visual presentation". The GUI usually consists of standard graphical components such as text boxes, lists, buttons, sliders and menus etc. The selection of these graphical components is mainly based on the user interface guidelines, and the nature of tasks. Shneiderman (Shneiderman 1992) advocates the use of such well designed and responsive interfaces in visualization environments to prevent erroneous input and to provide rapid feedback. Many successful examples are available, such as Dynamic Homefinder (Williamson & Shneiderman 1992), FilmFinder (Ahlberg & Shneiderman 1994) and LifeLines (Plaisant et al. 1996).

While using an interactive visualization environment, the main user tasks are navigation, object selection and object manipulation. In many cases, these tasks are achieved by directly interacting with the objects rather than requiring the use of graphical components in its user interface. This interaction style is called "Direct Manipulation".

Direct manipulation is a human computer interaction style that involves continuous representation of objects of interest, and rapid, reversible, incremental actions and feedback (Shneiderman 1983). There are different levels of direct manipulation and these levels are decided mainly by the interaction devices used in a particular visualization environment. We now give a quick overview of the categories of interaction devices.

1.3.1 Interaction Devices

Direct manipulation interaction style itself can be categorized by focusing on different aspects of interaction. There are different types of devices such as input devices, display devices, tracking devices, glasses that are used to serve different human senses, like stereo, etc.

Users can input their actions by using mouse and keyboard, by gazing or pointing towards any particular direction, or even by uttering commands. Users can view the "visual representation" on a variety of devices like desktop screen, head mounted display, 3D screens, retinal displays, panoramic screens, or by using virtual tables, and of course hard copy surfaces like paper.

Immersive visualization environments are those which support primarily the direct manipulation interaction styles. Immersive environment gives a user feeling of being in the visual environment where several of user's senses are isolated from the real world and are fed information (images and sound) from the computer. This submersion gives the feeling of direct manipulation where he/she can use physical actions to manipulate or navigate in the visual environment.

The interaction techniques and devices described in this section all work towards providing assistance to the user of the visualization environment in the comprehension of the underlying data or concept.

1.4 Validation

In engineering, every application, equation or model is usually checked for its validity and correctness with respect to a specified set of criteria. In software engineering, for example, this aspect of validation is gaining importance through the domain of software measurement and metrics for measuring the software quality. The same question can be asked about effectiveness of visualization environments in supporting comprehension. The main objective behind any visualization environment is to assist its user in gaining insight into the underlying information and making the information easy to comprehend. As mentioned earlier, in our research, we too propose to study the questions - what kind of evaluation can be done on visualization and what quality measurements can be applied to check how successful the visualization environment is in achieving this goal?

There are a few research groups around the world working on such evaluations. Mazur from MetaVerse lab who is working on the evaluation of immersive environments at University of Kentucky states the following about this issue: "A thoughtful and empirical analyses of transaction records will inform our understandings of HCI in immersive, non-restrictive environments where user's physical actions are symbolically related to their exploration and understandings of complex visualizations of information. Hence, preliminary research is needed to lay a sound foundation for suggesting areas for more systematic future research of immersive and non-restrictive environments (Mazur & Jaynes 2002). The bulk of the work presented by Microsoft Research in ACM SIGCHI 2005 focuses on the study of information visualization and how it can potentially change the way businesses, software developers and consumers process and organize information. The work is the result of collaboration with computer research scientists of more than 16 universities and several corporations from around the globe. (Microsoft 2005)

Our approach is to look at this problem of assessing visualization environments' effectiveness by considering the cognitive nature of "visualization". When abstract, non-visual data or a concept is represented visually, there are always intentions that visualization environment's developers have had in their minds, largely that users should be able to gain insight on certain aspect of the artefacts, relationships, processes or phenomena under study. On the other side, when users use any visualization environment, they use it with their specific goals and intentions. Now, our proposal is that effectiveness of visualization environment can be possibly measured if we can assess the extent to which these two sets of intentions match. In other words, we should check whether there is any information comprehension gap that exists between the visualization environment and its user. Can this gap be characterized by a set of criteria, the way in which software quality criteria have been identified? These issues and a proposed solution and empirical validation are the main focus of this research. While studying this problem, we limit our experimentation for empirical studies to 3D visualization environments, primarily because of the effort involved in carrying out such empirical studies.

1.5 Thesis Organization

The rest of the thesis is organized as follows:

Chapter 2 provides a review of literature and discussions that have in some way addressed this issue of evaluation of visualization.

Chapter 3 presents the visualization environments assessment problem as a comprehension gap between the visualization environments and user.

In Chapter 4, a list of "comprehensibility criteria" is proposed to describe the comprehension gap between visualization environment and the user and hence, to assess the comprehensibility in visualization environment. These criteria encompass the information "communication" intent of the visualization environment and the information "seeking" intent of the user.

Chapter 5 and Chapter 6 present two usability experiments on two different 3D visualization environments. They provide observations and descriptive statistics as the empirical evidence showing the relevance and importance of "comprehensibility criteria".

Finally, Chapter 7 summarizes the work, provides conclusions for this research and gives some directions for future work.

In addition, the two Appendices provide comprehensive information about the conduct of the two usability experiments.

Chapter 2: LITERATURE REVIEW

Much of the research and development emphasis in the field of visualization have been on devising new and computationally optimal techniques for managing the problems of creation, storage, updating and interaction present in large datasets, and of providing views (rendering visuals) of such large data. While the computational problems being addressed are indeed major challenges, the other equally important problem of assessing the effectiveness of the resulting tools and techniques needs greater attention. In this chapter, we review some of the discussions in the literature which also address this issue of a comprehension gap between the visualization environments and user.

It is not uncommon, these days, to see in major international conferences on visualization, a panel discussion topic for discussing the effectiveness of visualization, the challenges and the needs of measuring the effectiveness. Below, as representative examples of this, we shall briefly review the position papers of panelists of two such panel discussions held as part of IEEE Visualization conferences.

In the first panel discussion ('Panel: Metrics and Benchmarks for Visualization' 1995), the focus is on defining what a good visualization system is and how the visualization performance can be measured. Each panellist discusses the technical difficulties in obtaining accuracy in such measurement. Mike Botts ('Panel: Metrics and Benchmarks for Visualization' 1995) mentions that metrics for usefulness of a visualization environment are subjective and not easy to use. It involves measuring the intuitivism, accuracy, and easiness to use. He gives his views about the type of such metrics. According to him, such metrics should have general components applicable to any visualization environments and some components should be specific to a particular visualization environment. Another panelist, Sam Uselton argues that quality of visualization environment should be measured in the context of a purpose behind a visualization environment, and hence he thinks user testing provides the solution. He gives his outlook about the methods that can be used to make visualization environment trustworthy: objective methods to compare the accuracy differences, methods for displaying errors, methods for displaying the uncertainty measures in the visualizations. Other panelists, Jeremy Watson, Howard Watkins and Dave Watson then discuss in detail what should be the performance and accuracy benchmarks for the visualization environment in terms of graphical representations in the visualization environments.

The second panel discussion (Rushmeier 1997) talks further about the perceptual measures for effective visualizations. In this discussion, the agenda is to promote discussion of research and development needed for improving visualization effectiveness. In their statements, panelists express their opinion about the possible approach and the research done to devise the metrics for such effectiveness measurement. Panelist Holly Rushmeier states the importance of using information visualizations to obtain deep insight into the data and advocates the use of simple perceptual measures to assess the value of visualizations. Another panelist, Penny Rheingans raises interesting questions such as: Which vision attributes are most relevant to the visualization assessment? How can the knowledge about the human vision be used to measure visualization effectiveness? When should the general perceptual measures be overridden by the requirements of a specific domain? And lastly, how can such assessments be made useful in improving the overall effectiveness of a visualization environment? Each question by itself forms a potential topic for in-depth research. She further states the importance of experimental validation of such effectiveness and points out that to date such assessments are relatively rare. The last panelist, Sam Uselton, emphasizes that all the literature that describes what makes a good visualization is about communicating the known information. But, for the exploratory visualization environments, this paradigm is not applicable. He suggests that in order to build a set of measures for visualization effectiveness, we can begin by comparing and measuring the perceptual attributes of similar visualization environments, and then, can think about measures specific to each visualization environment.

Both the panel discussions address the issue of specifying and assessing the effectiveness of visualizations, but in a rather general fashion. What precisely constitutes this quality factor of 'effectiveness' is not very clearly defined in any of the discussions. Not withstanding this fact, they do give us initial pointers to categorize all related efforts reported in literature about assessing the effectiveness of visualization environments. In the following two sections we review two main research issues that the above discussions have alluded to: *assessment methods* and *assessment measures* for quantifying the effectiveness of visualization environments. For the assessment measures, panelists in the above discussions have repeatedly referred to perceptual measures that ought to be calculated. Hence, in the last section, we also review the literature that reports about some potential perceptual aspects that are studied in a specific type of visualization environment.

2.1 Assessment Methods for Visualization Environments

The main problem with assessment of information visualization environments is that there is no accepted standard practice in the field. The main methods used for such assessments can be considered to be one of the following kinds:

- Controlled user experiments to compare design elements of different tools,
- Expert evaluations using user interaction heuristics, and
- Observation studies in realistic settings.

There have been a few efforts at prescribing somewhat more formal assessment methodologies. These are briefly discussed below. A formal evaluation methodology for immersive environments has been proposed in (Gabbard 1999). This methodology consists of 4 sequential steps: analysis of user tasks, expert evaluation based on guidelines, observational evaluation based on the usage context, and comparative evaluation with other competitive environments. The author's claim is that the methodology helps throughout the immersive environment development process. A case study is presented where a battlefield visualization environment is evaluated using this methodology. Use of this methodology in the visualization development process is time consuming and effort intensive because each step requires preparation of many helping documents such as task scenarios, and guidelines for a specific immersive environment.

Another approach in (D. A. Bowman, Johnson, D. B., and Hodges, L. F. 1999a), suggests the use of test beds for evaluating user interaction in immersive environments. Here, the test beds are built up for immersive environments using a formal framework (D. and Hodges Bowman, L 1999b). Yet another paper (Winckler 2004) proposes scenario-based usability evaluation of information visualization environment.

Apart from such adaptations of usability methods for visualization environments, there are approaches that provide software tools to assess visualization environments. In (Mazur & Jaynes 2002), the authors describe a 3D visualization tool under development to analyze the immersive interaction data. A user transaction record is produced in terms of a graphical 3D representation and works as a supplement to the interviews, observations and survey data gathered to understand user requirements for immersive visualizations. In another approach, a cognitive model is used for such visualization evaluation - "Cognitive Architecture to Evaluate Visualization Applications" (CAEVA), being developed as an on-going project (Juarez-Espinosa 2003). It is proposed as an alternate solution to usability evaluations. CAEVA is a software architecture that describes the software components of the system built to evaluate information visualization environments. The cognitive model built is a major component of CAEVA and it is based on the knowledge about visualization, the data domain and data analysis strategies. Though this approach of evaluating visualizations claims to improve the assessment process, it has still many parts to be completed before it can really be used for visualization assessment. Central to its use is its requirement to build a cognitive model that is based on the collection of empirical data and knowledge about data analysis strategies. We see that currently both, such empirical data and documentation of data analysis strategies adopted by users are difficult to find.

Clearly, when it comes to assessing the effectiveness of visualization environments, from the point of view of information comprehension by users, evaluation methods are still in their infancy.

2.2 Assessment Metrics for Visualization Environments

Now, we shall look at some related literature with the main focus on what metrics should be used and what metrics must be calculated to quantify the effectiveness of visualizations. While we found it hard to locate a comprehensive set of metrics that are applicable in the assessment of visualization environments, we did find suggestions on a few interesting set of metrics in the published work,

In one of the panel discussions (Rushmeier 1997) referred earlier by us, Sam Uselton has proposed that we compare and measure the perceptual differences between the static images of two different visualizations. We review two papers that propose a set of metrics for such comparative assessment of visualization images.

In (Brath 1997), the authors present the result of their experience with 60+ 3D visualization tools as a set of four metrics: (1) number of data points and data density, (2) number of dimensions and cognitive overhead, (3) occlusion percentage, and (4) reference context and percentage of identifiable points. Here, they have two assumptions while collecting the metrics data: a static image of the 3D scene is considered while measuring these metrics and any interaction with the visualization is ignored. Though this set of metrics is a refreshing start towards generation of such metrics for visualization environment assessments, it does not address a very important part of visualizations: interaction and navigation of a 3D representation by user. In this paper, the authors themselves have mentioned that these metrics are not mature and that they need to be tested against a lot more number and types of visualizations for their correctness. Also, these metrics should be extended to accommodate interactions and navigation.

Another study in the field of image processing (Zhou 2002) focuses on the problem where the comparison is required for visual results from computer-simulated laboratory experiments. In science and engineering, such comparative evaluations of experimental results need to be done for their accuracy. For such comparisons, this paper proposes a set of image comparison metrics for quantifying the difference between a visualization of a computer simulation and a photographic image of a laboratory experiments. Though, this approach is not directed towards assessment of visualization environments, these metrics can prove to be effective.

In the earlier paper (D. A. Bowman, Johnson, D. B., and Hodges, L. F. 1999a), wherein the test bed approach is proposed, the metrics proposed for measuring the performance for different interaction techniques are (1) time for completion and accuracy, (2) characteristic of a task that determines the required accuracy, (3) number of objects in the environment, (4) spatial ability and (5) stereo or binocular viewing. They present two experiments where they collected data for these metrics and presented the results in terms of the interaction tasks.

From the above, we can see that there have been some proposals for metrics for assessing effectiveness of visualization environments and further validating them by collecting empirical data. In addition to the proposed metrics in the above efforts, some more perceptual factors that can prove to be helpful in the measurement of visualization environment assessments have also been studied. We present specific perceptual factors that have been considered in the next section below.

2.3 Perceptual and Cognitive Factors for Visualization Environments

In (Nakakoji 2001), cognitive effects of an interactive animated visualization are presented in the form of user study. In this paper, authors argue that autonomous motions in visualization produce certain cognitive effects and correct use of motions assist users in early stages of exploratory data analysis. In their user studies, they investigate: (1) in which cases autonomous motion proves to be effective and (2) how and when do users interact with an interactive animated visualization environment. In the first study, they use two data sets and three data representations for every data set. Three users view these representations and use think-aloud method to describe which aspect of representation they pay attention to. Cognitive factors frequently emphasized by the users are: breaking the data apart in pieces, interpreting data, grasping the whole data, expecting next, comparing data, statistically analyzing data, and filtering data. In the second study, an expert user is asked to view an animated visualization for an exploratory data analysis. It is observed that user first scans the whole animation and then uses the play-controller to have control on the time factor in that animation. It is also noticed that user uses color indicators as reference points to see sudden changes in data; user likes to have feeling of immersion to understand data dynamics; and user sometimes needs to know the context of the current snapshot with respect to the whole data. Even if these user studies are very preliminary and small, their importance lies in the fact that they propose a systematic approach to study cognitive effects of interactive animated visualization.

In (Smolnik 2003), the authors emphasize the use of right visual metaphors in visualizations so that users find "synergetic match" with human cognitive processes. In this paper, authors argue that visualization approaches are useful if visual representations of data aid a transformation to the human mental model. In this paper, they introduce visual perception theories and models that represent how the knowledge is stored in the form of mental representations. They present three visualization tools that they developed "to explore and navigate complete information space and create additional value, contexts and knowledge." Each of the tools use specific visualization characteristic: focus + context, layout styles, and support for motion perception respectively. Authors claim that their visualization tools amplify and accomplish cognition by using correct representations from the real world.

Abstracting from the above, it becomes clear that dynamism, visual metaphors and context in visualizations are significant cognitive factors to be considered in the assessment of visualization environments.

We shall now shift our discussion to user interaction in visualization environment by starting with an interesting paper (Hinckley et al. 1994) that talks about how user's natural interactions with the visualization environment results in better cognition. In this paper, it is studied how the user handles the real world three-dimensional objects in a specific problem domain and it is investigated how these gestures can be used as important means to interact with the visualization environment. This study is about using passive real world interface props for neurosurgical visualization. In this paper, neurosurgical planning is selected as a domain to demonstrate the usefulness of head-viewing prop, cutting–plane selection prop, and a trajectory selection prop. Neurosurgery happens in three-dimensional world; surgeons are always used to work with three dimensional structures and hence, authors claim that use of three dimensional props used as a three dimensional user interface offers a great solution. User's gestures are tracked by the trackers embedded inside the props and system responds and shows the visualization on the 2D screen. For example, head-viewing prop is a rubber sphere and is used to view and manipulate patient's head data; rotation causes corresponding rotation of a polygonal model of the patient's brain on the screen, and moving the prop towards or away from his or her body, causes the polygonal model to zoom in or out accordingly. This is a very innovative way of interacting with the visualization and authors claim that even if the user interface is demonstrated currently for neurosurgical planning, it can be generalized for other applications also. They present the obvious advantages of this type of interface: familiarity with the prop objects, direct manipulation to interact with patient data visualization, minimal training required to use this interface and immediate feedback of user actions.

As we shift our focus to the interactivity with the visualization environments, it must be noted that there are some new issues that need to be addressed with respect to human cognition. "Direct Manipulation Interfaces" are supposed to be more intuitive and direct, where users need less effort to interact with the visualization environment; immersive environments are based on this concept (Shneiderman 1983). It is expected that an immersive environment should offer a sense of naturalness in the appearance and interaction style. (Hu 2000) addresses the limitations of current virtual reality environments in accurately conveying the spatial information to the user and hence, they lack in offering a sense of naturalness to the visualization. The work reported presents the results of an experiment evaluating the effectiveness of visual cues when the user performs an object manipulation task in an immersive environment. In an experiment, four participants are given a head mounted display to wear, with the best commerciallyavailable image quality and stereo resolution. Participants stand at a physical table and manipulate a physical cylinder while viewing the virtual cylinder which moves in a manner coupled with the physical cylinder. The task accuracy and precision are measured in different setups where different combinations of a set of visual cues are present in the virtual cylinder. The results show that binocular stereo, shadows and inter-reflections help in determining the spatial information between virtual objects. Even with these visual cues, the accuracy and precision of such object manipulation tasks is not satisfactory. Hence, authors suggest that more work is required in performing controlled and quantitative examinations of perceptual accuracy in immersive environments.

In an immersive environment, another important cognitive aspect studied is: presence or the feeling of immersion. Immersive environment gives a user feeling of being in the visual environment where several of user's senses are isolated from the real world and are fed information (images and sound) from the computer. Presence can also be defined as "the extent to which the immersive environment has an appropriate effect on the user." (Nunez 2001) Whether the user really feels immersed in the immersive environment remains a topic of research.

In (Nunez 2001), the authors propose a cognitive psychological framework of measuring presence by stressing on its cognitive effect and propose a set of possible measures to measure it. Authors believe that it is more useful to focus on the effect of immersive environment on cognition than focusing on the sensations produced by the environment. They coin a term "cognitive presence" which is defined as "the degree to which the immersive environment dominates over the real environment as the basis for thought." For measuring cognitive presence, they propose a set of possible measures and hence, argue how measuring presence is a better quality factor than usability while evaluating immersive environments. Their subsequent paper (Nunez 2003) proposes that presence is an extension of perception and is a constructive process where users themselves construct the presence experience based partly on perceptual inputs and partly on the mental context as these inputs are processed. They support their claim with the results of a study in which 103 users participated. In this study, two immersive environments are created and each user is asked to read one of the two booklets: one related and one not related to the theme in the immersive environment they experience later. This study measures three variables: stimulus quality, conceptual priming and presence. First two variables are independent variables and are manipulated into two levels (low and high) the dependent variable, presence, is measured by means of three questionnaires. The results of the study shows that given a context, user sets the mindset about the theme before entering in the immersive environment; this affects their experience of presence. Even if the stimulus quality is observed to be directly effective in experiencing more presence, priming or giving context of the theme, works as a mediator variable in presence.

2.4 Discussion

As we have seen from the above review of literature related to the assessment of visualization environments, the studies are very diverse and assessment metrics and measures are often very specific to the domain of application or the technology/techniques being used in the visualization tasks. However, given the fact that the main purpose in all visualizations is communication of information, it is important to assess whether the "visual representations" in visualization environment are communicating the message and the extent to which they help the user in understanding the underlying information. In the next chapter, we propose a set of assessment criteria by collecting these many different independently studied cognitive factors and by using unifying principles from visual communication. Adapting from Norman (Norman 1998a), we present this assessment problem as a gap of evaluation and execution between visualization environments and human information processing capabilities. And then, we study each side of this gap with the use of existing models of a human information processor and a visualization system.

Chapter 3: COMPREHENSION GAP CHARACTERIZATION

In this chapter we present our approach towards characterization of the "comprehension gap" which determines the effectiveness of a visualization environment. Towards this goal, we have adapted Donald Norman's cognitive concept of gulfs of evaluation and execution. Based on this concept, we present the model for each side of this gulf: visualization environment and user's information processing capability. We try to investigate the possible reasons behind the existence of such gulfs by studying the characteristics of these models. By studying the nature of communication between these two sides, we propose to characterize the gap, between them, on the basis of two independent set of principles, Donald Norman's action cycle (Norman 1998a) and Aaron Marcus visual communication principles (Marcus 1995)

3.1 Understanding the Comprehension Gap between the Visualization Environment and User

When looking at the intentions with which developers developed the visualization environment and the intention with which user uses the visualization environment, we can clearly identify two sides: visualization environment and its user. If there is a difference, more precisely the "comprehension gap" between these two sides it can be identified as a "gap" or "gulf" between the two sides. This "gulf" is identified by Donald Norman in the context of understanding psychology behind using everyday things. (Norman 1988b) We adapt this cognitive concept to visualize the "cognitive distance" or gap between the user and the visualization environment. Donald Norman's principle about "cognitive distance" is based on two aspects of any human action: execution and evaluation. (Norman 1988a)

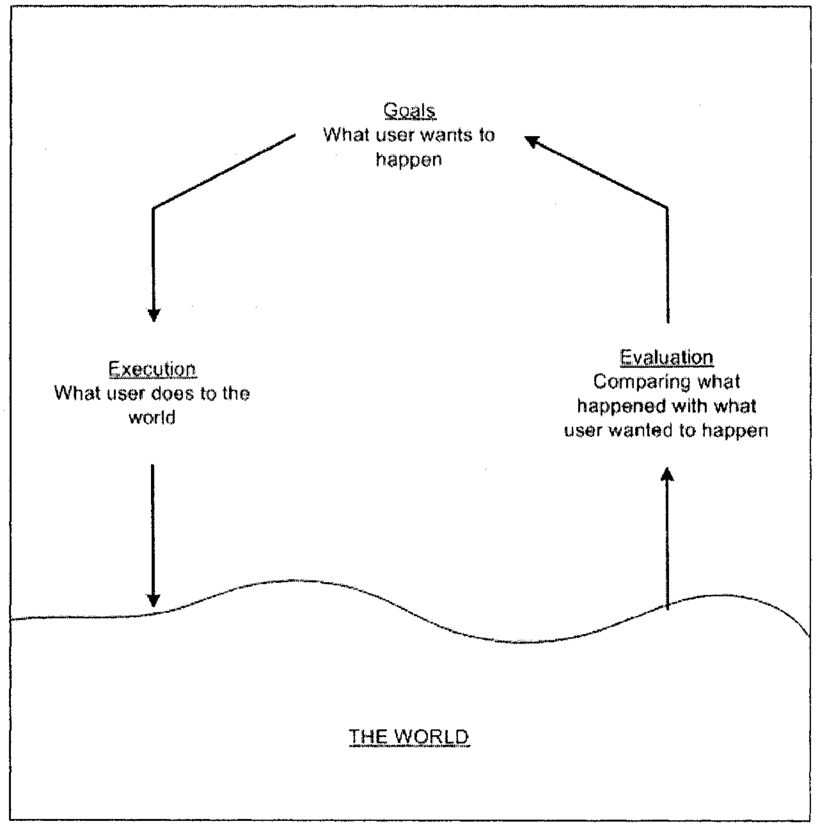


Fig. 3. 1 Two Aspects of Human Action

3.1.1 Norman's Seven-Stages Action Cycle

Donald Norman explains the "execution" as being what the human does to achieve a certain goal and "evaluation" as being the comparison that the human does between "what happened as a result of human actions" with "what the human wanted to happen" (Figure 3.1). (Norman 1988a) Norman describes further that any human action can be modeled using a seven-stage cycle: one for goal, three steps for execution phase and three steps for evaluation phase as listed below:

1. Forming a goal
2. Forming the intention to act
3. Specifying an action
4. Executing an action
5. Perceiving state of the world

6. Interpreting state of the world
7. Evaluating the outcome

These stages are pictorially illustrated in Figure 3.2.

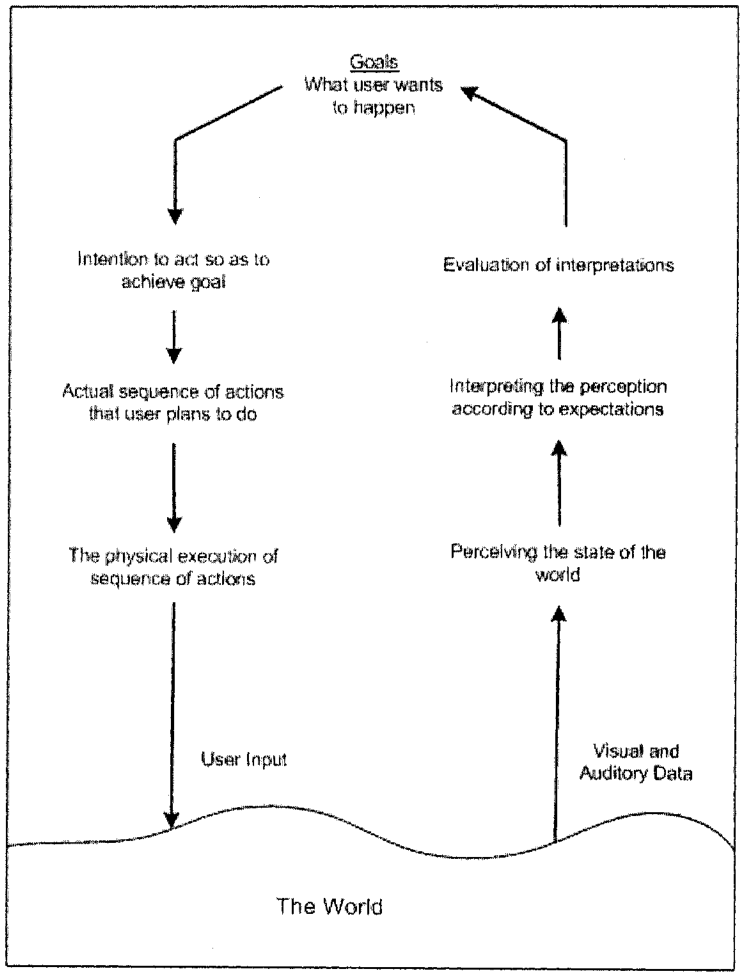


Fig. 3. 2 Norman's Seven-Stages Action Cycle

3.1.2 Donald Norman's Gulf of Execution and Evaluation:

Norman defines two gulfs that humans encounter while executing this seven-stage action cycle.

Gulf of execution: When user sees a system or device, he/she has some intentions to use it. Gulf of execution exists where user can't use the system or device using their intended actions. Thus, "gulf of execution" is the difference between the intentions of the users and what the system allows them to do or how well the system supports those actions (Norman 1988a).

Gulf of Evaluation: The gulf of evaluation is the degree to which the system/artefact provides representations that can be directly perceived and interpreted in terms of the human intentions (Norman 1988a). This gap exists when the system does not present itself to the user well enough for the user to understand the system state correctly and take the next appropriate right action.

Our premise is that smaller this gap, more effective is the human action in that environment in achieving the goals. We adapt this concept of gulfs of execution and evaluation to help us in modelling the "comprehension gap" between the visualization and the human information process as shown in Figure 3.3.

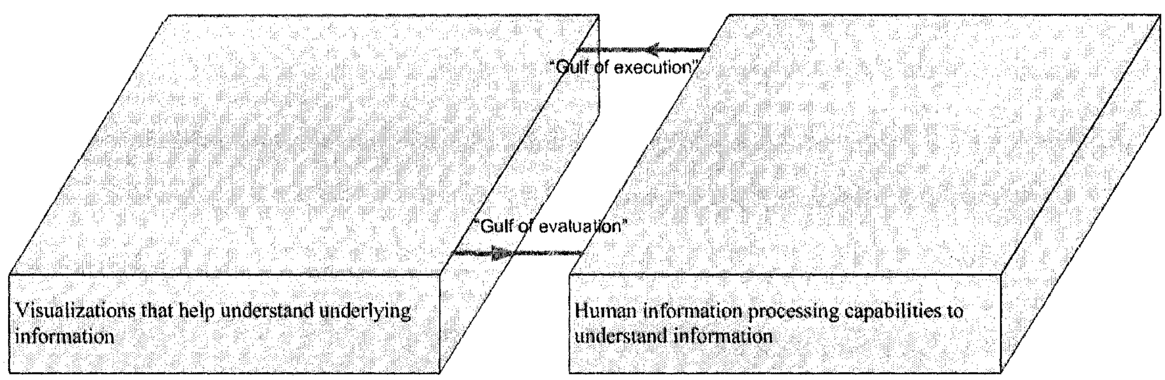


Fig. 3. 3 Model for Comprehension Gap Between Visualization Environment and User

On one side, there is a user who has certain information processing capabilities. He/she has certain goals and an intention of comprehending the information underlying the visuals rendered by the visualization environment. On the other side, there is visualization environment which represents the data under study in a visual form so that the user can process the underlying information in a visual way and manipulate this visual form to achieve certain goals. In this context, gap of execution exists when user's actions are not in interpreted as expected by the user. Gap of evaluation, in this context, exists when the user perceives the presented visual form incorrectly. Clearly, smaller the gap, more effective the visualization environment is, in terms of information comprehended by the users.

After visualizing this "cognitive distance" as "gap of execution" and "gap of evaluation", we need to characterize it in terms of further factors using applicable models for each side of the gap.

3.2 Understanding Human Information Processing Capabilities

In this section, we review some of the important human information processing models developed in the past including the "Model Human Processor" that we use for characterizing the comprehension gap.

3.2.1 Review of Human Information Processing Models

To understand how humans process the perceived information and process it to generate new responses, there are some theories and models that are developed in the field of cognitive psychology.

Since, the late 1960's, cognitive psychologists have drawn parallels between computers and human thinking, as both are involved in processing the information. The basic concept is that information enters and exits the human mind through a series of ordered processing stages. (Lindsay & Norman 1977) These stages are given in Figure 3.4.

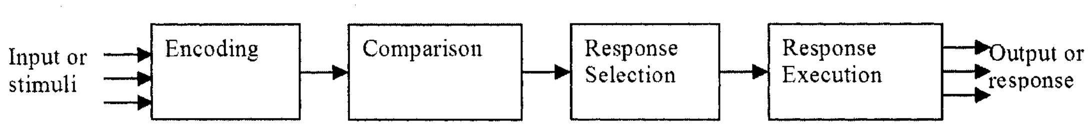


Fig. 3. 4 Human Information Processing Stages by (Lindsay & Norman 1977)

The two main extensions of the basic information processing model are the inclusion of the processes of attention and memory. With these add-ons (Figure 3.5), it becomes important to learn how information is perceived, how perceived information is attended to, and how it is stored in the memory (Barber 1988).

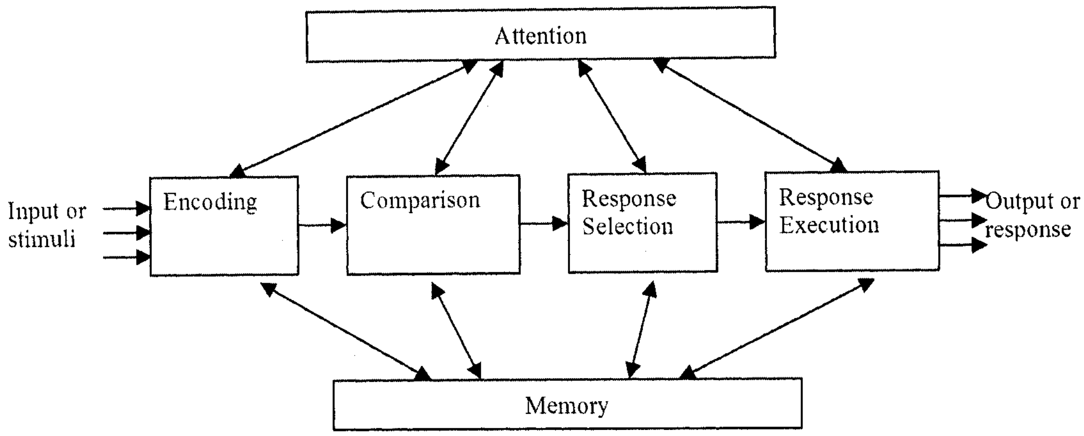


Fig. 3. 5 Extended Human Information Processing Model by (Barber 1988)

Now, we look at one more extension of original information processing model: "multi-store model of memory" (Atkinson & Shiffrin 1968). It explains explicitly why attention and memory play an important role in cognition theory. This model explains the 3 stages to record information into our memory (Figure 3.6).

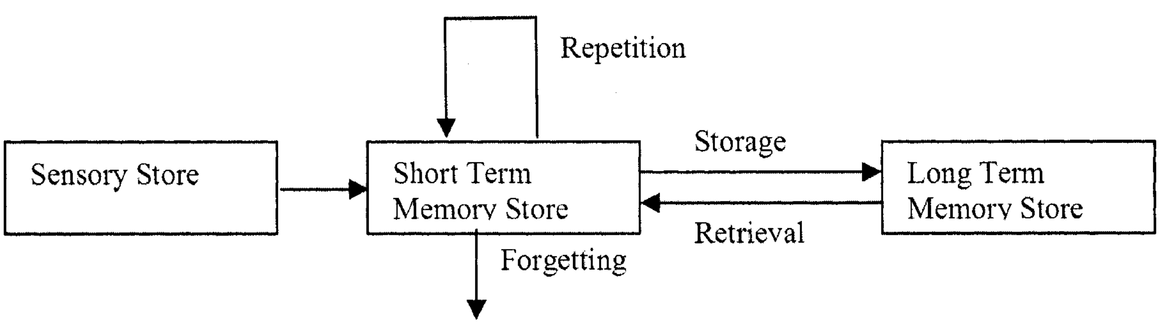


Fig. 3. 6 Multi Store Memory Model by (Atkinson & Shiffrin 1968)

According to this theory, there are different memory stores which are used at different stages of information processing. Our senses send a continuous stream of information to the human brain that is stored in sensory memory. But we do not remember all of it, because human brain does not process all of this sensory information to store it in the long term memory. But, only when we pay attention to this incoming information, it is stored in short term memory store in the form of an un-identified representation. To retain information in short term memory and also to pass it to long-term memory, frequent repetitions or rehearsals of this information representation is needed. As the number of such rehearsals increases, the probability of that information getting transferred to long term store increases.

3.2.2 Selection of "Model Human Processor"

After looking at how information processing models evolved, the model that we are going to use for further discussions is "Model Human Processor" by Card, Moran and Newell. (Card, Moran & Newell 1983) Their model has been chosen by us because it gives an integrated portrayal of psychological knowledge about human functioning as it is relevant to human computer interaction (Card, Moran & Newell 1983). "Model Human Processor" is comprised of a set of memories and processors together, and a set of principles of operation. Here, we discuss only the memories and processors of the model. Model Human Processor can be explained by three sub-systems: (1) the perceptual system, (2) the motor system, (3) the cognitive system. The information processing of the human is described as if there were a separate processor for each subsystem. We now briefly discuss these three processors and their interaction with the memory stores as is shown in Figure 3.7.

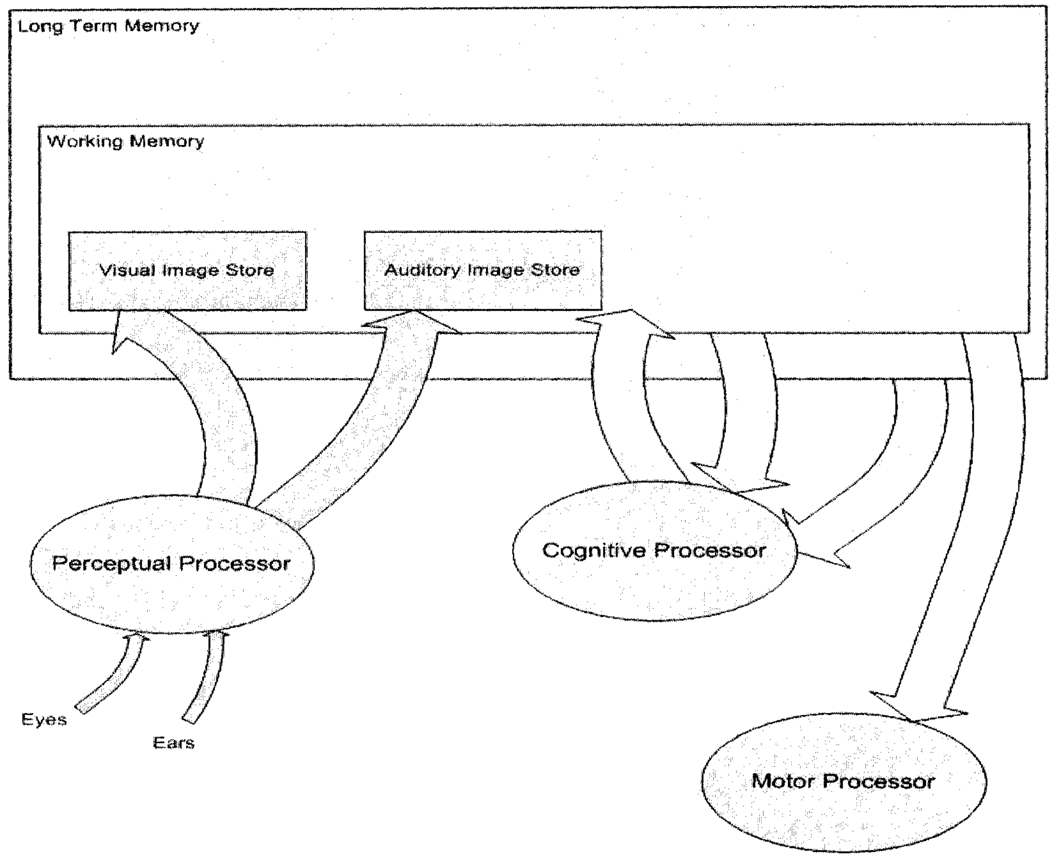


Fig. 3. 7 Model Human Processor by (Card, Moran & Newell 1983)

Perceptual processor receives the information from human sensory system, for example eyes and ears, and encodes it in un-identified symbolic internal representation and stores it in visual and auditory image store respectively. Cognitive Processor uses the working memory which contains visual and auditory image stores and is responsible for the higher level processing which includes decision making, reasoning and logical thinking. It retrieves the information in "working memory" and tries to match it with any of the stored representations in "Long term memory". Depending on the information matching, it takes the decision and conveys it to motor processor. Ultimately, motor processor generates a pattern of activities in relevant body muscles. Thus, we can see that, an analogy of human cognition to a computer system fits well as the three stages (input, processing and output) exist in both.

Out of these three processors, in psychology, there is a classic debate on our understanding of perception: role of the stimulus versus experience. The two main streams of perception theories are named as constructivist theory (Bruner 1966) and ecological theory (Gibson 1979). Out of these two, the influence of ecological theory of perception can be seen in Donald Norman's work on "affordances" of objects, devices, and computer interfaces. He, along with Gaver, (Gaver 1991; Norman 1988b) further argues that knowledge of affordances can be beneficial in reducing gulf of execution and evaluation (Preece et al. 1994a).

3.2.3 Perception Theories

To perceive is to become aware of through the senses. (*Oxford English Dictionary* 2005)

As discussed in "Model Human Processor", perception system gathers information from the human senses and stores it in the sensory memory buffers.

3.2.3.1 Constructivist Theory of Perception

Constructivism is a very broad conceptual framework in philosophy and science. Constructivist Bruner's theory represents one particular perspective. Bruner suggested that cognitive processes precede perception rather than the other way around; that a person may not perceive an object until he or she has recognised it. These cognitive theories of perception emphasise the role of knowledge in how we interpret the world (Bruner 1966). This constructivist approach is very influential in educational area. Bruner's theory is linked to child development research. It describes how children learn new concepts and develop their mental models about the real world.

3.2.3.3 Ecological Approach in Perception

Ecological approach by Gibson argues that perception is a direct process, in which information is simply detected rather than being constructed (Preece et al. 1994b). It opposes most traditional theories of cognition that assume past experience plays a dominant role in perceiving (Gibson 1979). Gibson proposes that the environment consists of "affordances" which provide the clues necessary for perception. Furthermore, the clues such as shadows, texture, color, convergence, symmetry and layout determine what is perceived. According to Gibson, perception is a direct consequence of the properties of the environment and does not involve any form of sensory processing.

Thus, both the perception approaches agree that humans are active perceivers. But, their point of view is very different. Constructivists say that we perceive by processing retinal images and making sense of it. Ecologists say that we actively look at the objects in our surroundings (by touching, tasting, seeing).

3.2.4 Mapping of "Model Human Processor"

Even if "Model Human Processor" is simpler than the actual rich and subtle human mind, it helps to understand human cognition relevant to human-computer interaction (Card, Moran & Newell 1983). If we map this model shown in Figure 3.3, "Model Human Processor" now represents user's information processing capabilities, as shown in Figure 3.8.

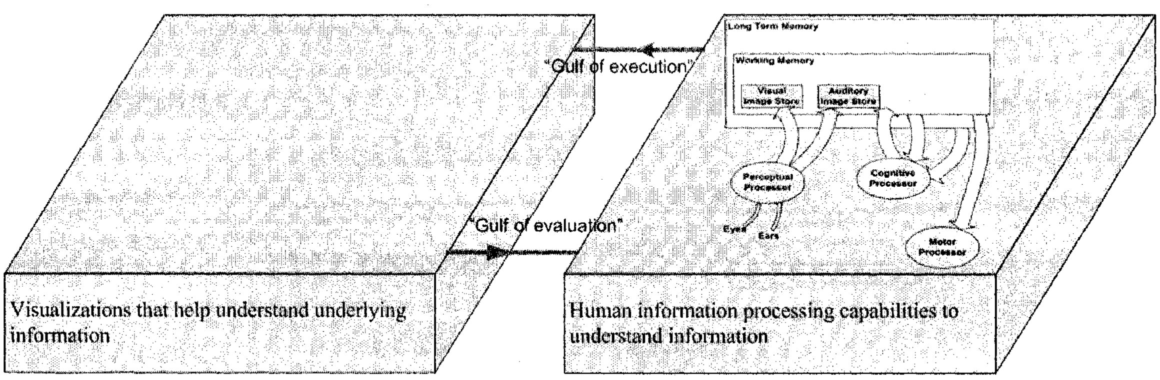


Fig. 3. 8 Mapping of "Model Human Processor" on "Model for Comprehension Gap"

3.3 Understanding Visualization Environment

Similar to human information processing models, it is important to find a model that can represent visualization environment side in Figure 3.3. Hence, in this section, we review various models and select a model that is most relevant to the human computer interaction domain.

3.3.1 Review of Visualization Environment Models

As first model to review, we consider "On-line Library of Information Visualization Environments (*On-line Library of Information Visualization Environments* 1997) described in the previous chapter, which is the taxonomy of visualization environments differentiated by data type (*On-line Library of Information Visualization Environments* 1997). Here, the main assessment criteria is stated as ""Overview first, zoom and filter, then details on demand" (Shneiderman 1992). This taxonomy categorizes the visualization environment but doesn't provide a model to represent a visualization environment. A framework based on visualization patterns (Wilkins 2003) talks about the visualization environments based on patterns. This framework provides methodology for visualization environment development and a set of visualization heuristics for their assessment. But again, it does not provide a generic model for the visualization environment. A model by Robertson and Ferrari (Robertson & De Ferrari 1994) portrays a detailed version of a visualization process (Figure 3.9).

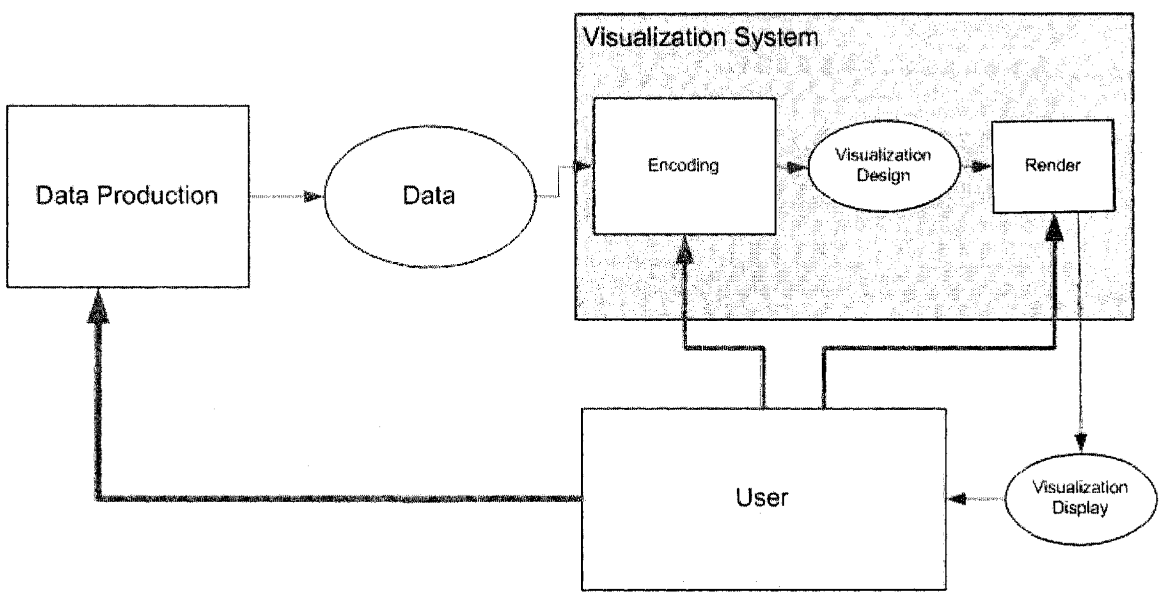


Fig. 3. 9 Visualization Model by (Robertson & De Ferrari 1994)

Robertson and De Ferrari describe six components of a "visualization system" that define its quality: data model, visualization specification, visualization representation, matching procedure, visualization display and interaction. (*Model of Visualization* 1999)

3.3.2 Choice of Model for Visualization Environment

For our purposes of characterizing the comprehension gap, we choose a model suggested by SIGGRAPH that depicts the same process mentioned above in the form of a set of abstract modules. Out of a set of abstract modules, if we consider a module "User Interface" and "User" modules, we can now model the visualization environment, from human-computer interaction perspective, as shown in Figure 3.10. The control is handled by the user and visual and auditory output data is presented to the user by "User Interface Module". (*Model of Visualization* 1999)

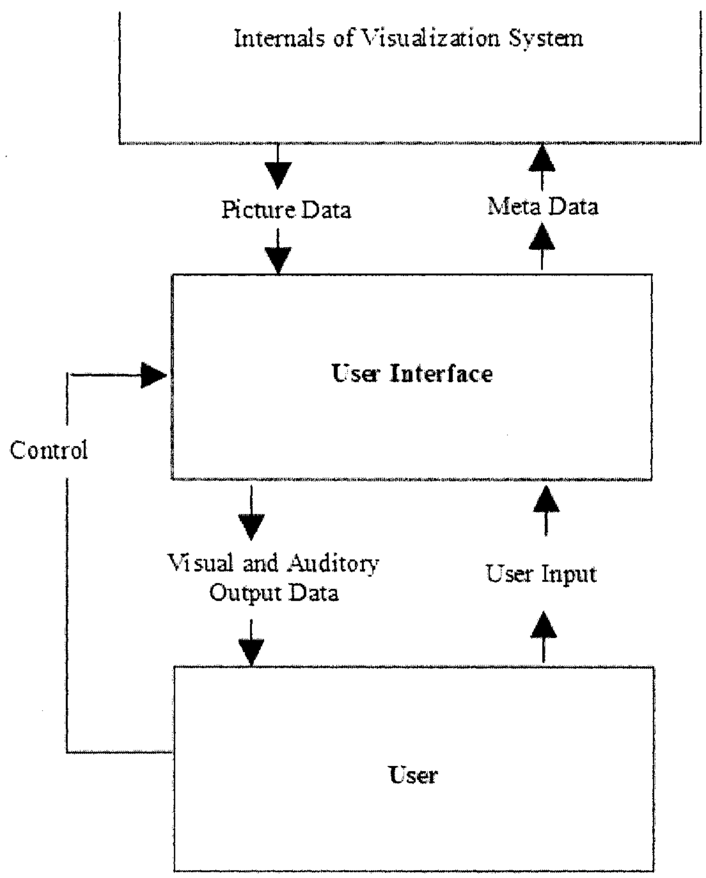


Fig. 3. 10 SIGGRAPH Model for User and User Interface Modules of a Visualization System

Here, from the perspective of user interface of a visualization system, we can see that there are three important components: data, visual representation of that data and user interaction with the visual representation.

3.3.3 Mapping of “SIGGRAPH Model for Visualization Environment”

If we refer to Figure 3.3 again, we can map this simplified “model of visualization system”, as depicted in Figure 3.11, to represent the visualization environment, in general.

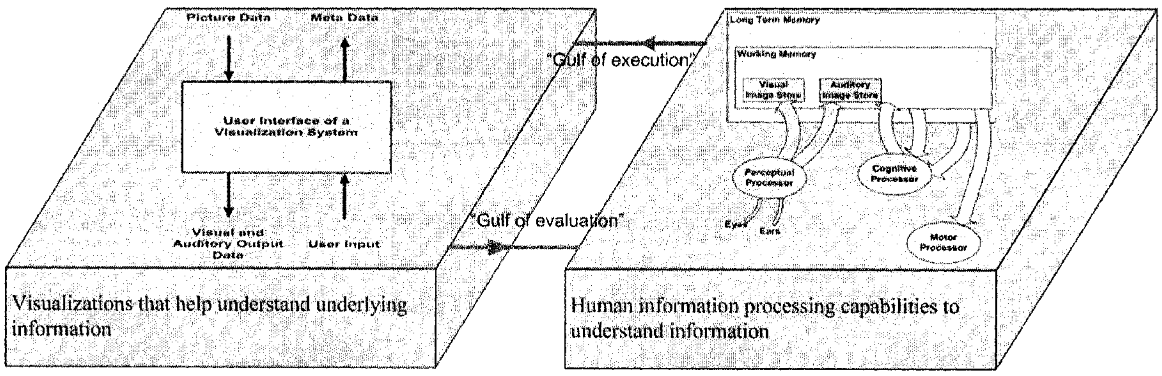


Fig. 3. 11 Mapping of “SIGGRAPH model of Visualization Environment” on "Model for Comprehension Gap"

After representing both sides by concrete models, as shown in Figure 3.11, we will now revisit Norman’s seven-stage action cycle.

3.3.4 Norman's Action Cycle Revisited

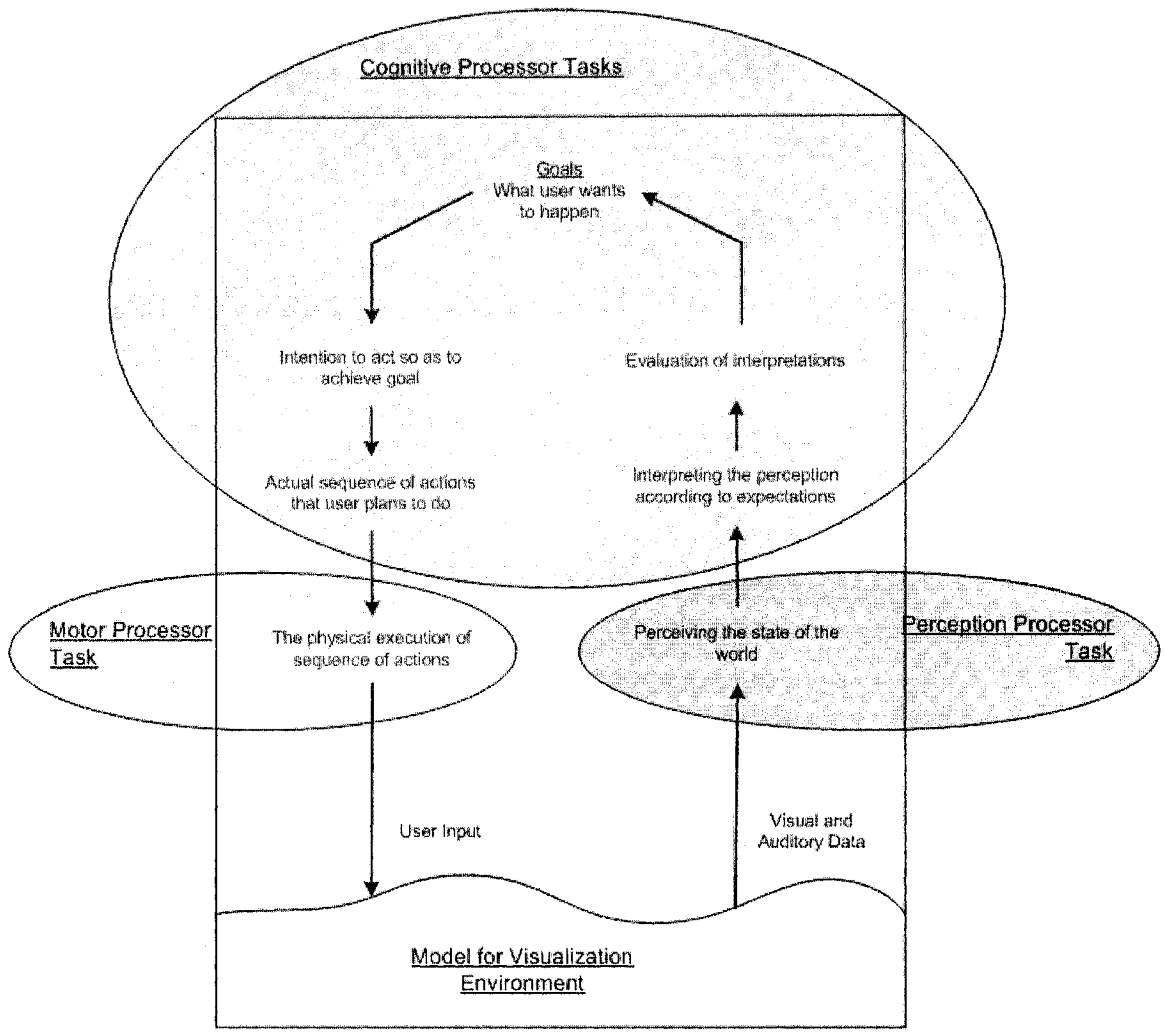


Fig. 3. 12 Norman's Seven-Stage Action Cycle Revisited

When we map both models on Norman's Seven-Stages Action Cycle, we see that "The World" is replaced by "Model for Visualization Environment". We can also observe how seven steps of the action cycle are distributed among three processors of "Model Human Processor". Physical execution of actions is carried out by the "motor processor" and perceiving the state of the visualization is performed by the "perception processor". All the rest are the cognitive tasks executed by the "cognitive processor".

3.4 Communication between Visualization Environment and User

Our next goal is to study the communication between the two models. In this section, we first explain the communication process between visualization environment and the user in terms of senders and receivers, and the type of messages exchanged between them; and then, we propose two sets of principles that can be used to characterize each of these models and hence the communication between them.

3.4.1 Communication Process

Referring to Figure 3.11, we can clearly identify the following: User takes action and the visualization environment reacts to user actions. This communication can be studied in terms of sender, receiver and a message (visual messages generated by visualization environment and user actions by users).

When there is a problem in this communication process, gap of execution or evaluation can get created between them. Nature of this communication problem decides the nature of this "gap". If user cannot interpret the "visual message", it results in gap of evaluation; when user takes incorrect actions, it results in gap of execution. To characterize the communication gap in terms of certain quantifiable parameters, we propose two sets of principles.

3.4.2 Application of Visual Communication Principles

By definition, "Visual" is anything that can be seen by human eyes (*Oxford English Dictionary* 2005). Visuals can be letters or numbers, or objects in the physical world. When the communication using visuals is studied, it is called a study of "Visual communication" (Barry 1997).

Principles of visual communication have been developed to propose the ways of developing effective visual display of information. As logical extension, these principles can also be used to assess how effective the "visual message" is to communicate the information to the user.

Though visual communication is a very large field with very specialized interests, we have selected a set of principles proposed by Aaron Marcus because of their relevance to human-computer interaction. As a specialist in graphics design, he recommends a set of principles and rules that a graphical user interface should follow in order to be effective (Marcus 1995). His principles are:

1. Organize: Provide the user with a simple, clear, consistent conceptual structure
2. Economize: Maximize the effectiveness of a minimum set of cues
3. Communicate: Match the presentation to the capabilities of the user.

Although, these principles are presented to improve the user interface design, since a visualization environment is also interactive in nature, these principles can also be used to to assess the nature of "visual message" generated by visualization environment. In the next chapter, we define all these principles while presenting collective set of comprehensibility criteria for visualization environments.

3.4.3 Application of Cognitive Principles

As explained in section 3.1.1, we see that a physical action can be explained in the terms of Norman's seven stages of human action. By taking into account these seven stages, Norman presents a set of cognitive principles as an aid to reduce gaps of execution and evaluation. Norman states that visible affordances, constraints and correct mappings, feedback, and positive transfer effect are the concepts that should be followed to help human actions in achieving their goals. He mentions that these same concepts effectively help in reducing the gap of execution and evaluation. Hence, we propose that, along with the visual communication principles, this set of cognitive principles is important in achieving effective communication. Each of these principles is defined in the next chapter along with Marcus' visual communication principles in formulating the collective set of comprehensibility criteria.

3.5 Summary

In this chapter, we studied the gap between visualization environment and the user in terms of Norman's gulfs of execution and evaluation. To define each side of this gap, we reviewed some significant models and chose the relevant ones for each side of the gap. We then studied the nature of communication between these two models and hence, proposed to apply two set of principles to characterize the gap between these two models. In the next chapter, we present these principles and underlying concepts as a collective set of "comprehensibility criteria".

Chapter 4: COMPREHENSIBILITY CRITERIA FOR VISUALIZATION ENVIRONMENTS

In this chapter, we present a set of "Comprehensibility criteria" for modelling the gap between visualization environment and its user by combining two sets of principles from cognitive psychology and visual communication.

The visual communication principles introduced by Aaron Marcus have been formulated to assure the visual message quality in the context of user interface design (Marcus 1995). According to him, an information-oriented, systematic graphic design helps user understand the complex information. As mentioned in the pervious chapter, in order to achieve effective visual communication, he suggests the following three principles: organize, economize, and communicate. As a logical extension, these "design principles" are also helpful in assessing the user interface for its effectiveness in visual communication.

In each visual communication principle, we propose to add some more concepts from cognitive principles introduced by Donald Norman. Donald Norman mentions a set of principles: affordances, constraints, mappings, feedback, and transfer effect as a design aid for better user interactivity. We provide definition for each of the concepts and according to the role, we add it under one of the visual communication principles.

4.1 Use of word "Comprehensibility Criteria"

The word "comprehensibility" means quality of being comprehensible. The verb "to comprehend" itself is a vague term to determine.

To comprehend is to grasp with the mind, conceive fully or adequately, understand, 'take in'.

The information "seeking" intent of user is the comprehension process that user's mind engages in when he/she uses a visualization environment. In other words, "visual message" generated by visualization environment should follow certain principles or concepts so that it is "comprehensible" by its user. This eventually helps in minimizing the gaps of execution and evaluation. Hence, we use the term "comprehensibility" to identify these concepts.

Use of the term "criteria" comes from the usability model, (Padda 2003), where there are three levels of usability measurements: factors, criteria and metrics. Out of these three, "Quality criterion" is an attribute of the quality factor that defines the product. Thus, "criteria" are observable goals; their measures can be collected by using one or more metrics. Hence, we call the following collection of concepts as collection of "comprehensibility criteria" for visualization environments.

In the following sections, we introduce each principle of visual communication introduced by Aaron Marcus, and the concepts included under them. For each concept, we present its definition, the reason for why is it useful in characterizing the "visual message" and lastly our goal in validating the usefulness of that concept.

4.2 Organize

This principle is stated as follows:

"Provide the user with a clear and consistent conceptual structure"(Marcus 1995)

We can adapt it to say that organize the "visual message" so that the user gets a consistent and clear conceptual model of the visual presentation.

In case of a visualization environment, the presented information is a visual representation of a non-visual concept, or data or objects. This principle indicates that this presented information should have certain characteristics so that it is unambiguous to perceive and understand.

There are number of criteria under "Organize", introduced by Aaron Marcus in the context of user interface design. We decided to adapt "Consistency", "Navigability" and "Relationships" as they are in our opinion the relevant ones for a "visual message" generated by a visualization environment.

4.2.1 Consistency

Definitions:

- Oxford dictionary meaning is being constant to same principles.
- Aaron Marcus defines 4 types of consistencies: internal, external, real world consistency, and inconsistency. (Marcus 1995)

Reasoning:

Internal consistency: apply same conventions and rules to all the elements of the visualization environment.

External consistency: use same conventions and rules in all visualization environments of the same type.

Real world consistency: make the conventions consistent with the real world experience.

Inconsistency: deviate from the existing conventions only when doing so provides clear benefit to the user.

These criteria are fairly general and abstract. Still, they have to be the basic rules to be considered by any user interface or any visualization environment.

Validation:

Validation is possible by observing and noting user comments about any internal and real world inconsistency. External consistency is out of scope as we are not comparing different visualization environments.

4.2.2 Navigability

Definitions:

- To navigate is to manage or direct the course of. (*Oxford English Dictionary* 2005) It is often given in the context of a ship or an aircraft.
- Other definition is the ability to steer through the affording passage.

Reasoning:

When we see this criterion in terms of visualization environments, navigability is user's ability to steer through the environment and environment's ability to direct the course of user's navigation.

Aaron Marcus suggests that a visualization environment must provide initial focus for the viewer's attention, must direct attention to important, secondary and peripheral items and also assist in navigation throughout the environment. (Marcus 1995)

Validation:

For the validation, users may be asked to rate the visualization environment's assistance for navigation. User's comments may also be noted while he/she is using the environment.

In addition to these two criteria, we propose to add some more criteria according to the study of visual perception of a human.

4.2.3 Clustering

Definitions:

- To cluster is to form into or be in a bunch of similar things. (*Oxford English Dictionary* 2005)
- One more simple definition of "Clustering" is identifying similar characteristics and grouping cases, with similar characteristics, together.

Reasoning:

Clustering is added to respond to Gestalt's theory of human perception. According to Gestalt's laws of perceptual organization, (Lowe 1985)

1. Elements that are closer together tend to be grouped together (Proximity);
2. Elements that are similar in physical attributes, such as color, orientation or size, are grouped together (Similarity);
3. Elements that lie along a common line or smooth curve are grouped together (Continuation);
4. There is a tendency for curves to be completed so they form enclosed regions (Closure);
5. Any elements that are bilaterally symmetric about some axis are grouped together (Symmetry);
6. Elements are grouped together if we are used to seeing them together (Familiarity).

Validation:

Some of the interesting observations that could be made are: whether users detect:

- Objects that are close to each other in the environment,
- Objects of same color, orientation or size,
- Objects lying along the common line,
- Familiar group of objects.

4.2.4 Affordance

Definitions:

- According to Gibson (Gibson 1979), who coined this term, affordances are the actionable properties between the world and an actor. For him, affordances are relationships.
- According to Donald Norman, real and perceived affordances are the perceived and actual fundamental properties of the object that determine how it could possibly be used. (Norman 1988b)

Reasoning:

Affordances provide strong clues to the operations of things. When affordances are taken advantage of, the user knows what to do just by looking. (Norman 1988c) Hence, making affordances of a visualization environment perceptible can help to make it easy to use (Preece et al. 1994b).

Validation:

During use of the visualization environment, one can observe which affordances user perceives and tries to use. It determines ability of a visualization environment to provide such clues about its usage.

4.2.5 Constraints

Definitions:

- Constraint is the exercise of force to determine or confine action; coercion, compulsion.
- In POET, Donald Norman introduced the distinctions among three kinds of behavioural constraints: physical, logical, and cultural. (Norman 1988b)

Reasoning:

Physical constraints: are closely related to real affordances of a visualization environment.

Logical constraints: use reasoning to determine the alternatives. Logical constraints are valuable in guiding behaviour. If the fundamental design model behind a visualization environment is made visible, users can readily (logically) deduce what actions are required.

Cultural constraints: are conventions shared by a cultural group. A convention is a cultural constraint: it prohibits some activities and encourages others. Conventions are not arbitrary: they evolve, they require community of practice.

Validation:

One can observe whether there are any obvious physical constraints required by the visualization environment. Then, as logical constraints go hand in hand with a good conceptual model, (Norman 1988b) One can observe user's behaviour to find out whether they follow any logical constraints. It is also important to observe whether there are any conventions that rule user's interaction with the visualization environment.

In addition to these criteria, referring to one of the past studies described earlier in Chapter 2 about perceptual effects of visualization environment on users (Nakakoji 2001), we propose one more important criterion to be added under "organize" principle - "dynamism".

4.2.6 Dynamism

Definition:

- Dynamism is a dynamic action, according to Oxford dictionary. (*Oxford English Dictionary* 2005)
- According to the study (Nakakoji 2001), animation in a visualization environment is an autonomous motion of the visualization along the time dimension.

Reasoning:

According to (Nakakoji 2001), animation in visualization environments can be of two types:

1. *Motions of existing objects:* In case of scientific visualization, a concept or a phenomenon is modeled based on reality and visualized using computer graphics technology. When an animation is used to represent the changes in the model according to changes in data over time, it helps user to understand what is or what will be happening about that concept; for example, visualization of a hurricane course.
2. *Motions to represent changes in abstract data:* When an animation is used in the second type, where motions represent the changes in abstract data, the intention is not to model the real concept, but to help user's understand the hidden meanings and trends in the abstract data.

Validation:

User's reactions and comments about the dynamism in the visualization environment can be noted. We want to know the significance of dynamism in the visualization environments and its effects on its users.

4.2.7 Depth Perception

Definitions:

- Depth perception is "the ability to perceive relative distance in space." (*Oxford English Dictionary* 2005)
- It is the ability to see the world in 3-D, even though the image focused on the retina is flat. (Norcia 2005)
- Visual depth cues are studied by understanding human eye's functioning. This ability, to perceive relative distance in space, comes by interpreting the size, shape, shadows and overlap (monocular depth cues), as well as the small discrepancy difference in the images received by each eye (binocular depth cues). (Cron 2005)

Reasoning:

For the visualization environments that need more than two-dimensions, there is a physical constraint of using a two-dimensional screen on which the visual representation is displayed. So there is a need to simulate the effect of depth (the third dimension) with the help of visual depth cues.

There are two ways to render the depth on two-dimensional screen (Huk 1999; Vince 2004):

1. Use of monocular depth cues such as linear perspective, size ingredient, height in the visual field, shading, occlusion, atmospheric blur, and motion parallax. Some of these depth cues are selected and incorporated in the visual representation.
2. Use of binocular depth cue: horizontal disparity. It is achieved by using interaction devices such as glass filters, HMD screens etc. that create two separate views of the visual representation for two eyes. This disparity in the both eyes gives the information about depth.

Validation:

In three dimensional visualization environments, it becomes important to see how users perceive depth. Users can be asked to rate the effectiveness of visual depth cues in their understanding of the visual representation. User's behaviour according to the effects of different depth cues can also be noted.

4.2.8 Collection of "Organize" criteria

All the above criteria are grouped under the principle of "organize" as shown in Figure 4.1. The goal behind using this set of criteria is to characterize the quality of "visual message" sent by visualization environment to its user and to ensure whether the visualization environment is providing a clear and consistent conceptual structure to the user.

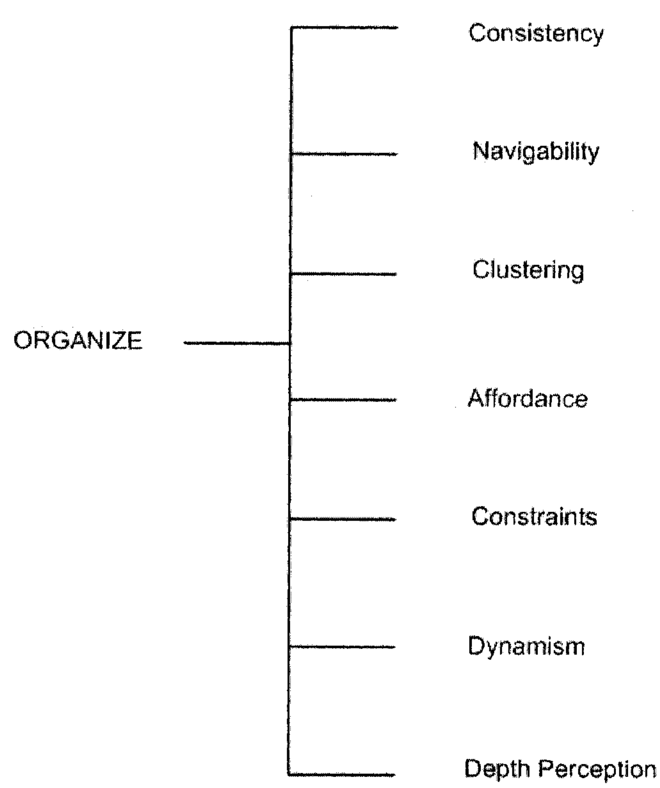


Fig. 4. 1 Set of Criteria under "Organize" principle

4.3 Economize

This principle states that:

"Maximize the effectiveness of a minimal set of cues."(Marcus 1995)

Here, we try to collect a set of criteria that assess the "visual message" for the usage of minimum number of visual cues and creating the maximum effect. Marcus ensures that it is achieved when a visualization environment does well with respect to the following concepts: simplicity, clarity, distinctiveness, and emphasis. (Marcus 1995)

4.3.1 Simplicity

Definition:

- According to Oxford dictionary, simplicity is the quality of being uncomplicated.
- According to Aaron Marcus, simplicity is to be unobtrusive. He suggests that we include only those elements that are essential for communication.

Reasoning:

This criterion is a desirable quality of any visualization environment. But, it also depends on the intent with which the visualization environment is created. When the intention is to confuse, entertain, or beautify, simplicity cannot be the factor to determine the effectiveness of a "visual message" it is communicating.

Validation:

While validating this concept as a criterion for assessing visualization environment, we first understand the intent behind that particular visualization environment and whether simplicity is the desired property. If yes, then, we see whether user feels confused anytime or any unnecessary information is being shown to the user.

4.3.2 Clarity / Intuitiveness

Definitions:

- Clarity is the quality of being readily perceived or understood.
- Another definition is "free from obscurity and easy to understand; the comprehensibility of clear expression."

Aaron Marcus proposes that all the components of a visualization environment should be such that their meaning is not ambiguous. This requirement is very general for direct use. Hence, we propose to use intuitiveness instead.

- Intuitiveness is defined as having perceived by immediate apprehension without reasoning.
- One more definition is "being spontaneously derived from or prompted by a natural tendency." Intuitiveness is a desired quality for any user interface.

Reasoning:

As intuitiveness is more discussed and studied concept in human computer interaction domain, we decided to consider "intuitiveness" over "clarity" as a potential criterion of a "visual message" generated by visualization environment.

Intuitiveness also is a relative term. According to the user's past experience and knowledge, certain things may or may not be intuitive to the user.

Validation:

Right now, at this exploratory stage, when we are exploring the characteristics of an effective visual communication between visualization environment and the user, we plan to note down what are the aspects or interactions with the visualization environment which are intuitive to the users. By studying these aspects, we can learn more about "intuitiveness" in a visualization environment.

4.3.3 Distinctiveness

Definition:

- Distinctiveness is the quality of being distinctive; distinctive force, tendency, operation, effect, or character.
- Being distinctive is having a distinguishing mark or quality; a characteristic.

Reasoning:

This criterion needs further investigation as to what makes essential elements of a visualization environment distinctive. In a visualization environment, the visual representation as well as the interaction methods can have some distinct features that make them stand out.

Validation:

As this characteristic is not studied much in previous work, we plan to observe what distinctive tendency, operation, effect or characteristic of the "visual message" makes them distinctive.

4.3.4 Emphasis

Definition:

- Oxford meaning of this word is "importance assigned to, a particular fact or idea".
- To emphasize is to lay stress upon, bring into special prominence (a fact, idea, feature etc.)

Reasoning:

Under the concept of navigability, Marcus mentions about providing initial focus for the viewer's attention, and directing attention to important, secondary and peripheral items. This would require:

1. Making the most important elements prominent i.e. easily perceived;
2. De-emphasizing non-critical elements;
3. Minimizing clutter so that critical information is not hidden".

Validation:

We want to observe whether such emphasis affect's user's attention. After they experience the visualization environment, we ask them to name the elements they paid attention to, and the ones that they didn't see easily. We match this user experience with the intention behind designing the visualization environment. This explains how emphasizing on critical elements change user's understanding.

4.3.5 Collection of "Economize" criteria

Fig 4.2 shows this set of criteria grouped under the principle of "economize". This set of criteria ensures that user is now provided with a concise form of a "visual message" which is intuitive along with being economical.

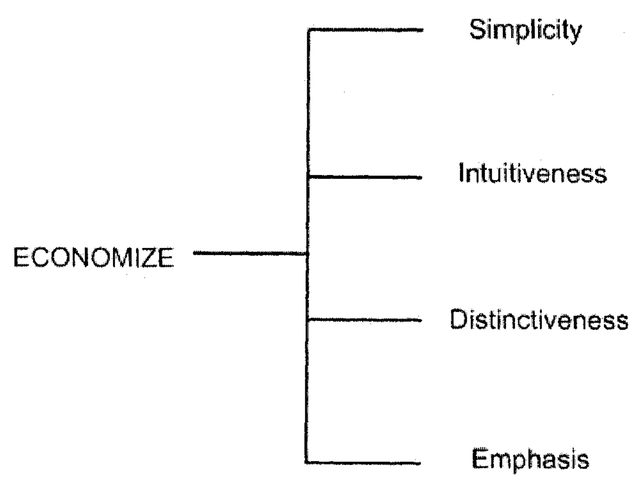


Fig. 4. 2 Set of Criteria under "Economize" principle

4.4 Communicate

The third principle for effective visual communication says that:

"Match the presentation to the capabilities of the user." (Marcus 1995)

In this principle, we characterize the communication characteristics of "visual message". We enlist the set of criteria that make sure that the "visual message" sent by the visualization environment matches with the capability of human cognition.

Model Human Processor describes the user's capabilities. It explains how the human perception, cognition and motor processor work with the help of attention and memory stores to understand the "visual message" transmitted by the visualization environment. Apart from organizational and optimization aspect of "visual message", it is also important that the message is actually reaches the users in the right manner. For this, Aaron Marcus has proposed the following criteria: legibility, readability, multiple views and effect of color.

4.4.1 Legibility

Definition:

- Dictionary meaning of this word is "the quality of being plain enough to be read; or condition of being easily made out or deciphered". (*Oxford English Dictionary* 2005)
- According to Aaron Marcus, individual characters, symbols, and graphic elements should be easily noticeable and distinguishable. (Marcus 1995)

Reasoning:

Even though visualization environments are about the visual representations, sometimes, they use some literal forms like characters, numbers to name different parts of the visual representations. Combination of graphic elements with such literal elements can sometimes makes it difficult for user to comprehend the message collectively. This can be due to poor typography, layout, overlap etc.

Validation:

Such difficulties will emerge in the form of user's complaints about legibility problems and these can be recorded.

4.4.2 Readability

Definition:

- Oxford dictionary meaning is "the quality of, or capacity for, being read with pleasure or interest, considered as measured by certain assessable factors, as ease of comprehension, attractiveness of subject and style". (*Oxford English Dictionary* 2005)
- Aaron Marcus states that the visual representation should be comprehensible i.e. easy to identify and interpret, as well as inviting and attractive. (Marcus 1995)

Reasoning:

Ability of a visualization environment to make the "visual message" readable, i.e. easy to read and interpret depends on two major factors.

1. *User's prior knowledge:* If user has prior knowledge and experience about the nature of "visual message", the visualization environment is presenting, then of course the ease of interpreting the "visual message" is more.
2. Visual message's quality of being interpretable: But, attractiveness and ease of comprehension of a "visual message" also depends on the quality of "visual message" itself. Apart from the characteristics discussed under organize, economize, the visual representation itself should be the correct one.

We present one example from our usability study here describing these two factors. In DNA visualization software, the trajectory of a DNA sequence is being presented to the user. If user has worked with DNA sequences before, he/she can identify the presentation and can try to comprehend it.

Apart from this factor of past knowledge, it is also important whether showing a trajectory of DNA sequence is a correct visualization.

Validation:

"Perception processor" in Model Human Processor (Card, Moran & Newell 1983) perceives and encodes the information, "Cognition Processor" decides the action depending on the memory stores contents, and "Motor processor" actually executes this action or set of actions.

With this background about user's capabilities of interpreting the presented visual presentation, we propose a validation technique to judge the user's interpretation. We propose to judge the user's interpretation by noting down the physical action taken by this processor. As cognitive processor is responsible to decide the interaction with the visualization environment, user's actions can speak volumes about how user interpreted the visual representation.

During the validation, we plan to note down all the important actions taken by the user that are suggestive of user's interpretation of the visual representation and the state of the visual representation itself. This way, we can get an idea about how the user reached the decision of making this particular action. This proposal is still a very preliminary and we need to validate it by verifying it with the actual observations.

4.4.3 Symbolism

Definition:

- The practice of representing things by symbols, or of giving a symbolic character to objects or acts. (*Oxford English Dictionary* 2005)
- The systematic use of symbols; hence, symbols collectively or generally.
- Aaron Marcus suggests that icons, symbols used in visual presentation should be carefully selected and refined to communicate the desired contents. (Marcus 1995)

Reasoning:

The symbols used in the "visual representation" map certain information about the underlying concept or data. If such symbolism is used in any visualization environment, it should be assessed whether the correct symbols are used.

Validation:

We plan to observe if users notice any symbolism or metaphors in the visualization environments. We also plan to see whether the symbols used are helpful for them to understand the underlying information.

4.4.4 Multiple views

Definitions:

- A view is defined as a formal examination or inspection of something, made by a properly appointed or qualified person; (*Oxford English Dictionary* 2005)
- Aaron Marcus suggests providing multiple perspectives on the visual representation of complex structures and processes. An important principle of good graphics design

requires making use of these multiple views for displaying visual representations. (Marcus 1995)

Reasoning:

Here we try to explore different types of "visual messages" that can be initiated by a visualization environment.

1. There can be different forms of visual representations of the same concept or object. Each visual representation shows different aspect of that set of data.
2. There can be different levels of abstraction to show the same concept, data or object. For example, software architecture is an abstract concept. Its visualization can be either in the form of the module/component level or of the code level.
3. Sometimes, looking at different views of an object simultaneously gives the user clearer idea about an object's structure. For example, in any 3D object modeller software, a classical view includes top, front, left, and isometric views of a 3D object shown simultaneously.
4. The relationships, links and the cross references between different parts of the data can be shown in different views. For example, in business data visualization software, the business data that has geographic links is shown in a separate view and other relationships among unlimited business dimensions are shown in different views.

Validation:

We note down user's comments, request them to mention the importance of having such views and ask them to rate this feature.

4.4.5 Effect of Color

Definition:

- The dictionary meaning of color is the quality or attribute in virtue of which objects present different appearances to the eye, when considered with regard only to the kind of light reflected from their surfaces. (*Oxford English Dictionary* 2005)

- Color is a graphic element of any graphics design. Each color has meaning and symbolism. It is the critical factor in the success of the visibility and readability of visual representations. (Marcus 1995)

Reasoning:

With respect to learning and comprehensibility, color is superior to black and white in terms of the viewer's processing time and emotional reactions. Color can work better towards communicating facts, concepts and emotions, if used correctly. With respect to memory performance, memory for color information appears to be superior to black and white.

Aaron Marcus discusses the importance of color in non-verbal communication. He says that color can emphasize important information; it can identify subsystems and structures; it can portray natural objects realistically; it can reduce error of interpretation; it can add coding mechanism; it makes visual presentation appealing. In a visualization environment, color is an added dimension that can stir up moods and make powerful statements when used wisely.

Validation:

We want to know the effects that different colors used in a visualization environment generate. Hence, in the validation study, we observe the effects of using specific colors in the visualization environment. We note down user's reactions and the colors, that they specify when asked about the colors they saw in the visualization environment.

After this set of criteria, we also propose to add some more criteria gleaned from our study of literature on visual perception and cognition process of the user.

4.4.6 Mapping

Definitions

- Mathematical meaning of mapping is a correspondence by which each element of a given set has associated with it one element (occasionally, one or more elements) of a second set. (*Oxford English Dictionary* 2005)

- In the context of visualization environments, mapping is a technical term meaning the natural relationships between two things: action and effect. It is a relationship between users' actions and their effects on the visual representation. Norman states that mapping problems are the fundamental causes of difficulties. (Norman 1988a)

Reasoning:

Visualization environment has its own set of mappings already designed in it. For each specific action by user, visualization environment is set to respond in some form. If this mapping is correctly understood by the user, user takes right actions to interact in a specific way.

Sometimes, these mappings are told to the user before using the environment. Still, if these actions are not the most natural ones for the user, user takes incorrect action. As Norman says, natural mapping requires least amount of effort from user's side in deciding the action to interact. Hence, the correct mappings in the visualization environment become the characteristic of the "visual message" generated by a visualization environment.

Validation:

We plan to record any such mapping difficulties when users are using the visualization environments. We also ask the users about their natural actions to interact with the visualization environment. This way, we can assess, how correct the visualization environment is, in creating the mappings.

4.4.7 Responsiveness

Definition:

- Responsiveness is the quality of being to be answering or replying.
- Sending the information back to the user about what action is done and what is the result of that action is a well known concept in control and information theory. It is an inherent requirement for any kind of communication or the message passing to happen.

Reasoning:

In a two way communication between visualization environment and the user, now the response from the visualization environment on user's actions also becomes the "visual message" for the user. The changed visual representation, with respect to the user actions, becomes the next "visual message" for the user. Hence, it is needed to study this criterion to judge visualization environment's effectiveness in creating new "visual messages", as the responses to user actions.

Validation:

We plan to ask the users about the quality of the response by the visualization environment and ask them to rate this responsiveness.

4.4.8 Contextualization

Definition:

- Contextualization is the act or result of contextualizing; studying anything in contexts. (*Oxford English Dictionary* 2005)
- When a structure, composition is made up by the combination of elements, the parts which immediately precede or follow any particular element determine its meaning or the "context". (*Oxford English Dictionary* 2005)

Reasoning:

This characteristic is influenced by the use of "focus + context" or "overview + detail" technique used in user interface design (Shneiderman 1992). In the visualization environment, often, user wants to view a particular part of the complex visual representation in detail while keeping its context visible. For this purpose, user often uses the zooming technique in the visualization environment. By doing so, now, along with the focused part of the visual representation, user sees the context in either of the two ways:

1. The preceding and following parts of the visualization, or
2. User's relative position in the overview of the whole visual presentation.

This helps user to view the focused part of the visual representation in detail, by keeping track of the context.

Validation:

We want to study how user understands the context when he/she zooms-in on a particular part of the visualization. We note down user's reactions when he/she loses the context or feels lost in the visualization environment. We also request users the usefulness of seeing the context.

4.4.9 Collection of "Communicate" criteria

The collection of criteria under "Communicate" principle of visual communication can be summarized as shown in Figure 4.3.

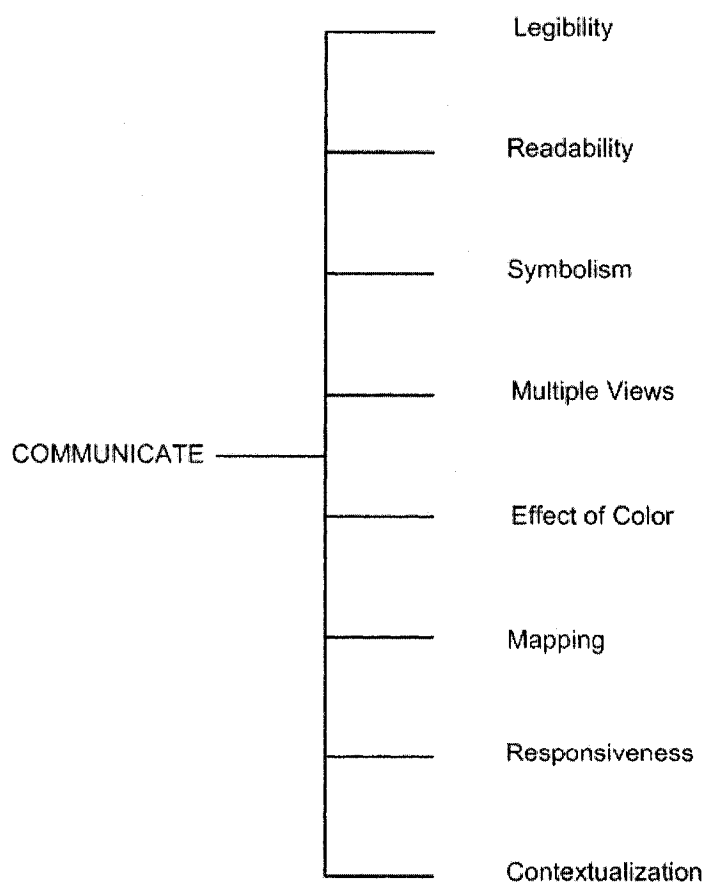


Fig. 4. 3 Set of Criteria under "Communicate" principle

4.5 Collective Set of Criteria for Visualization Environments

To summarize, in this chapter, we present a first attempt to characterize the entire visual communication process and hence the comprehension gap between visualization environment and the user. The principles of visual communication have been chosen as a foundation. Norman's cognitive principles have also been included as a part of these comprehensibility criteria under different principles. This has yielded a collective set of assessment criteria for comprehensibility in visualization environments and shown diagrammatically in Figure 4.3.

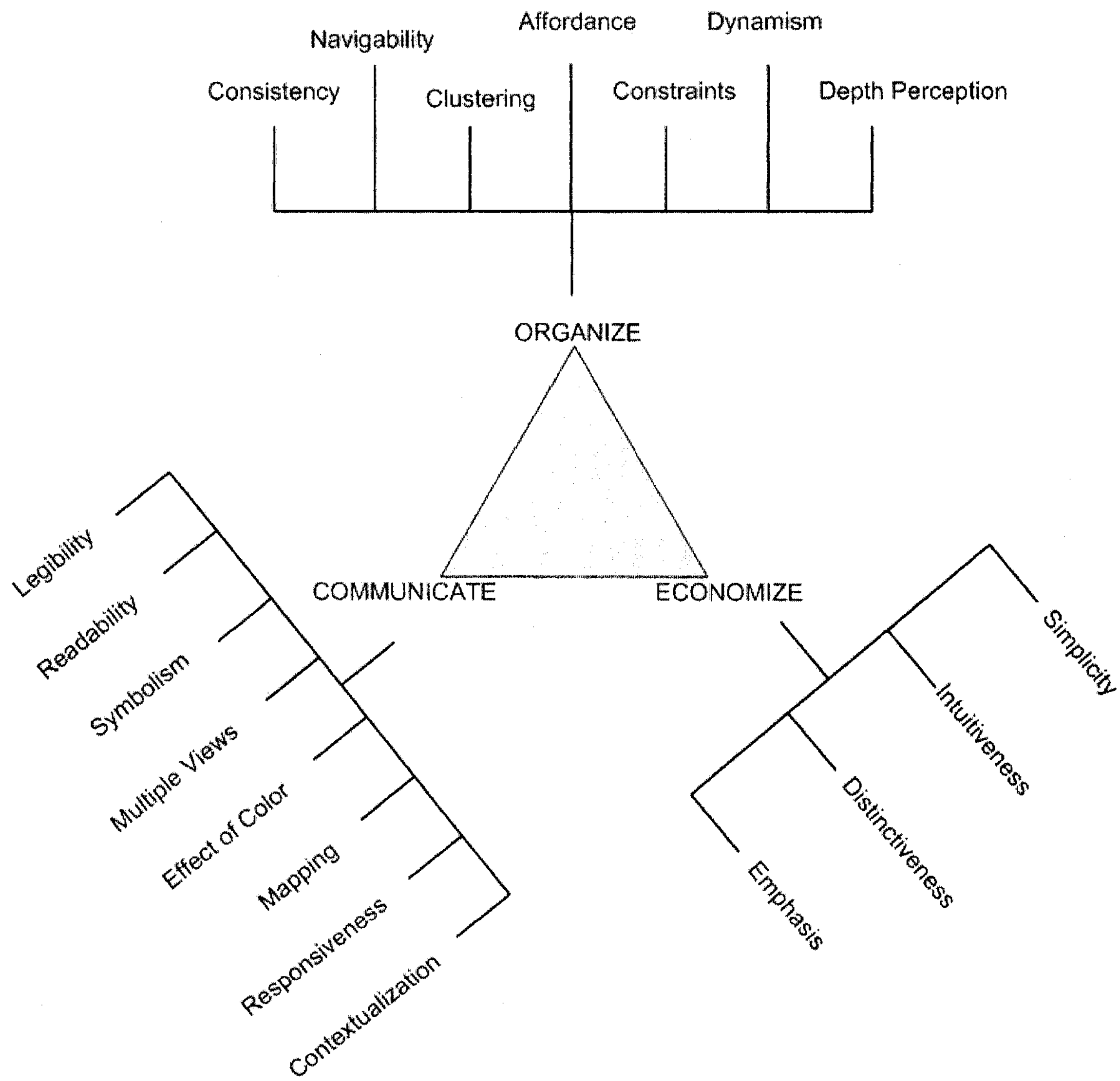


Fig. 4. 4 Proposed Set of Assessment Criteria for Comprehensibility in Visualization Environments

A comprehensive view of this combination of two sets of principles is illustrated further in Table 4.1.

Table 4. 1 Mapping of Aaron Marcus and Donald Norman principles onto one collective set

Aaron Marcus Principles of Visual Communication	Collective Set of assessment Criteria for Comprehensibility in Visualization Environments	Donald Norman's Principles from Cognitive Psychology
Consistency	Consistency -Internal -External -Real world	 -Transfer effect
Screen Layout		
Navigability	Navigability	
Relationships	Clustering	
	Affordance	Affordances
	Constraints	Constraints - Cultural standards
	Dynamism	
	Depth Perception	
Simplicity	Simplicity	
Clarity	Clarity/Intuitiveness	
Distinctiveness	Distinctiveness	
Emphasis	Emphasis	
Legibility	Legibility	
Readability	Readability	
Typography		
Symbolism	Symbolism	
Multiple Views	Multiple views	
Color/Texture	Effect of color	
	Mapping	Mapping (Comfort)
	Responsiveness	Causality/ Feedback
	Contextualization	

In the above table, the middle column presents the collection of concepts from both the sets on its left and right. In this table, we observe that screen layout and typography are not included in the collective set because their definitions are very specific to "user interfaces" rather than being specific "visual messages" or "user actions". Also three criteria, mentioned in blue color are the criteria that we are proposing to add in the set after reviewing the research papers related to such assessments, as given in Chapter 2.

4.6 Experimental Validation

In the validation studies, we plan to empirically substantiate our choice of concepts to characterize the gap between visualization environment and its user. To achieve this, we observe the communication process between visualization environment and its user. Specifically, we note down the user actions and characteristics of "visual messages" generated by visualization environment. Apart from these observations, we ask specific questions to the users that indicate the relevance and importance of "comprehensibility criteria" we proposed in this chapter. In the following two chapters we describe these usability experiments and present the findings in terms of descriptive statistics.

Chapter 5: CASE STUDY I - OSMOSE

This chapter presents our first usability study of an immersive visualization environment for the validation of criteria proposed in Chapter 4.

Usability testing is a well supported method for such assessment, according to the literature covered in Chapter 2. We had this rare opportunity to have a real immersive environment available for conducting such tests. In this chapter, we present the details of an immersive environment, details of the usability study and the detailed analysis on the collected data. Finally, we present our conclusions and the learning from the study.

5.1 Immersive Visualization Environment: OSMOSE

"Osmose" is a virtual artwork of Canadian Artist, Char Davies. It is an immersive environment where 3D immersion is achieved by using head mounted display (HMD) and interaction with OSMOSE is accomplished with the use of body movements and breathing. Since its introduction in 1995 at the Musee d'art contemporain de Montréal, OSMOSE is still exhibited in various art museums around the world. (*Immersence* 1995-2005)

Access to such a well recognized immersive environment was possible because of HMD project, initiated by Dr. Sudhir Mudur. In the first phase of HMD project, a usability study of this immersive environment, and specifically the study of head mounted display (HMD), was scheduled at Concordia University. The system was installed in Department of Computer Science at Concordia University for around one month in May 2005. HMD usability study was conducted by the team of "Human Centered Software Engineering" group under the supervision of Dr. Seffah. Apart from the scheduled HMD usability study, we conducted one more study of OSMOSE to assess this immersive visualization environment specifically for studying the visual communication process and hence, validate the "comprehensibility criteria".

5.2 Artist's Description of OSMOSE

The artist's intent in creating OSMOSE is to "reaffirm the role of the subjectively experienced, 'felt' body in cyberspace." One other article writes about *Osmose* as follows: "It makes the physical self—rather than the conscious mind—the locus for participant interaction. By doing so, Davies allows us to be affected by a virtual space in the same subtle way that we are shaped by our unconscious apprehension of our actual, physical environment." (Davies 2001)

5.3 Using OSMOSE

OSMOSE is a virtual world that any person can explore and experience. Char Davies calls the participant as, "immersant". To explore OSMOSE, a person wears the HMD and the vest with the help of technicians. The vest and HMD, when not being used are shown in the Figure 5.1 below.

Fig. 5. 1 Head Mounted Display used in OSMOSE

As a 15-minute OSMOSE session starts, first the user encounters the 3D Cartesian grid that helps the user to get comfortable with the navigation actions. After a while, he/she smoothly enters OSMOSE. Depending on his/her breathing actions and body movements, he/she travels through different parts of this virtual world.

5.4 Comprehensibility Study of OSMOSE

5.4.1 Goal

The main goal behind this study is to observe the communication process between the 3D immersive environment and the participant. This first hand experience gives rich information about the interaction between participant and the environment and how this affects participant's comprehension of the artwork. We want this first study to throw some light on whether we are proposing the right set of criteria to assess the visual communication between visualization environment and the participant.

5.4.2 Objectives

1. Study the post test questionnaire responses to understand some of the relevant criteria mentioned in Chapter 4.
2. Study the visualization environment's responses to user actions and understand environment's effect on participant's interactions.
3. Study the participants' OSMOSE sessions and understand the human information processing behind the participant interaction.

5.4.3 Constraints in the study

1. In this study, the main constraint is the domain of this immersive environment; we do not intend to assess the quality of the artwork; hence, the comments made about OSMOSE are only for the purpose of Comprehensibility Study.
2. Fixed 15 minutes time of one OSMOSE session. We cannot measure the "time for task completion" as the time to explore OSMOSE is set by the artist only. We can only note down the comfort level that participant achieved at the end of OSMOSE session.

5.4.4 Tasks

OSMOSE is a virtual artwork that is exhibited in a museum. According to the artist, Char Davies, "immersant" should freely explore OSMOSE with his/her own intuitions and actions. Hence, there is only one task for the participant, which is to experience and explore OSMOSE for 15 minutes (as intended by the artist).

5.4.5 Participants

Fifteen participants were invited for "Comprehensibility Study of OSMOSE'. Three of them are repeating participants who also took part in an earlier "HMD study" with the same experimental set-up. In addition, we had also requested participants of "HMD study" to fill out the post test questionnaire of "Comprehensibility Study of OSMOSE". Ten of them responded to our request and sent their responses some days after their OSMOSE experience.

5.4.6 Usability Testing Process

Formal usability test sessions were executed by following the methodology given in appendix A (Li 2005). All the details about conducting these tests are given in Appendix A. It includes the process of contacting participants and preparing test schedule, the description of physical test environment, roles and responsibilities, navigation actions, samples of all the test documents and the individual comments and interview highlights of the actual test sessions.

5.5 Understanding visual communication between OSMOSE and participant's "Model Human processor"

Here, we present the visual communication scenario between OSMOSE and the participant. As introduced in Chapters 1 and 3, the visualization environment communicates with its user in the form of "visual message", and responds to user actions by changing or creating the "visual message". In OSMOSE, "visual message" is one of the virtual "world spaces" designed by Char Davies. (*Immersence* 1995-2005) On the participant side, "Model Human Processor" (Card, Moran & Newell 1983)represents participant's capabilities to process the "visual message" communicated by the visualization environment. Its perceptual processor encodes and stores the perceived visual information in the "visual image store". When this perceived information is attended to, "cognitive processor" retrieves this information from "working memory" and with the help of any related stored representations in "long term memory", takes the decision about the next action or set of actions and conveys it to "motor processor". "Motor processor" actually executes the action or set of actions. This complete scenario is illustrated in Figure 5.2 below. The figure shows a simplified version of OSMOSE to keep the visual communication process in focus.

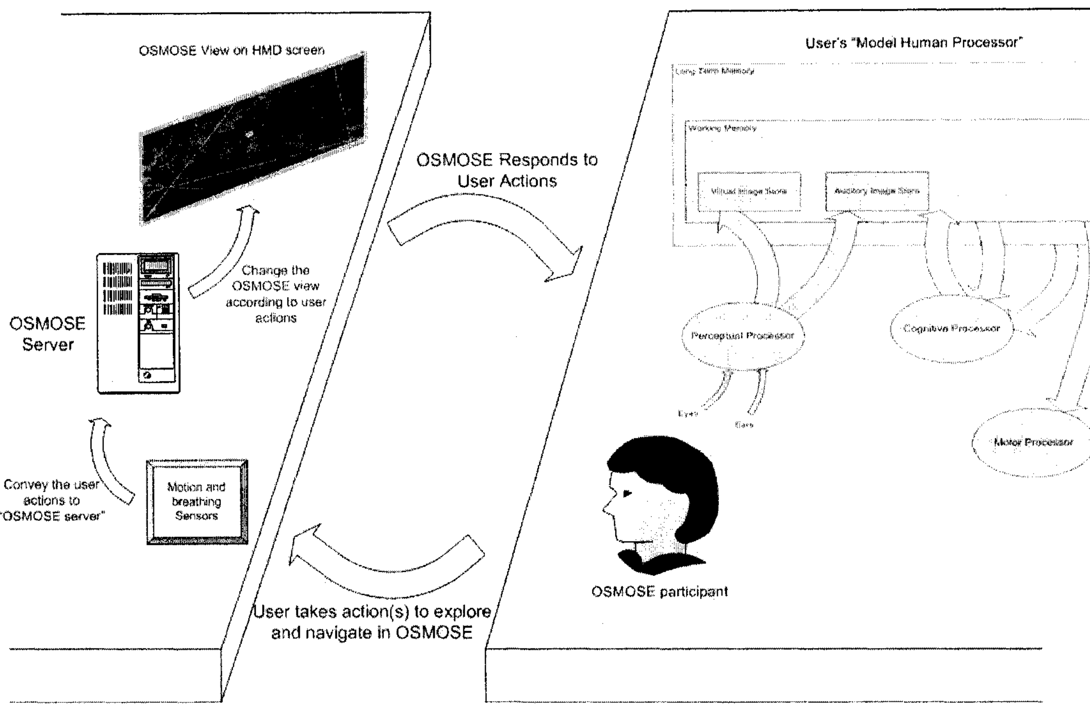


Fig. 5. 2 Visual Communication between OSMOSE and user

Now, we try to see the same visual communication scenario from the point of view of proposed criteria and actual test session. Participant wears the HMD and vest with the assistance from "monitor". He/she first sees the 3D grid on the HMD screen. As they are instructed about the navigation actions that can be used, they are asked to use them while looking at the grid. OSMOSE responds by changing the scene accordingly. Here, participants get their first introduction to the **responsiveness, navigability** of OSMOSE and **mappings** of their actions with their respective effects on OSMOSE.

Slowly, OSMOSE begins to appear on HMD screen and participant can hear the background sounds through the HMD headphones. Now, participant looks at the OSMOSE elements and decides to take a specific action to go towards any particular direction. Now, in this perceptive and cognitive processing, many organization and economization characteristics of the "visual message" may be responsible. Real world or internal **inconsistency, clustering, affordances**, physical and logical **constraints, dynamism, distinctiveness and emphasis** can be some influential characteristics of OSMOSE's "visual message". As participant takes actions, OSMOSE visualization environment responds by changing the "visual message" seen by participant on HMD screen.

This exploration task is repeated by the participant throughout the 15 minutes. During this communication, many communication characteristics such as legibility, readability, effect of color, mappings and responsiveness decide on the quality of the communication.

In the next section, we summarize the results from our questionnaires. As discussed in Chapter 4, we try to gather observations related to specific "Organize, Economize and Communicate" criteria.

5.6 Summary of Observations and User Comments

We summarize all the user comments and observations according to their relevance to each criterion defined in Chapter 4. For some of the criteria, we also borrow results from HMD study as they are relevant here.

5.6.1 Consistency

OSMOSE is an artwork which tries to be innovative and hence, different than the real world. It uses some natural elements from the real world, like tree, leaves, rocks, sounds of birds, and some other visual elements like texts of source code or commentaries on the art. But, at the same time, it makes it inconsistent from the real world elements in the way that these elements are transparent or semi-solid, *glowing* as mentioned by many participants. Also, in OSMOSE participants notice that there is no stable surface or ground on which you can stand; there is always a feeling of "out of body" experience, as mentioned by one participant. There is no sense of touch or collision detection when participant passes through any object like tree, rather when they pass through some object, the scene changes.

Thus, there are lot of real world consistencies and inconsistencies observed at the same time in OSMOSE. Many of the interesting comments about this are listed in Appendix A.

5.6.2 Navigability

In HMD, the navigation depends on user actions: breathing in and out to go up and down, looking around by turning head and leaning forwards and backward to move in the respective direction. Hence, navigability of OSMOSE depends on the effectiveness of these actions to navigate. We received some comments and suggestions from the participants about navigability in OSMOSE. Highlight of the comments was their attempt to understand how they can navigate and in OSMOSE, what are the rules for navigability. Some found out that the navigation path is circular; some discovered that tree is the central point and also an entry point to another world. The comments are listed in the Appendix A.

5.6.3 Clustering

There are some obvious clusters observed in OSMOSE. Green leaves and the white light sources tend to get the attention. Some participants try to look at the leaves closely because of their "proximity" or follow the white light sources or "bugs" as "they were placed in a line". These perceptual laws of organization seem to help in understanding and recognizing the group of elements while exploring OSMOSE.

5.6.4 Affordance

Some of the physical affordances of OSMOSE are: (1) HMD with headphones: By looking at the screen and headphones, you know that you are going to see something and hear something. Screen affords looking and headphone affords hearing voice. (2) Vest: It affords stretching and loosening. So, it affords action that does that.

Apart from these, there are some interesting perceived affordances observed during the study. (1) Whenever user sees text in OSMOSE, it affords reading. Though, it is not clear whether the text and source code in OSMOSE is intended to be read, many participants start or try to read it. (2) Some participants thought that the ground they see at one level in OSMOSE affords landing on it or touching. One participant commented as "(OSMOSE) should have sense of stationary ground", "when I found ground, I tried to land on it, and I sort of fell through it."

5.6.5 Constraints

As per the definitions of constraint from Chapter 4, there are three behavioural constraints or compulsions: physical, logical and cultural constraints. There are lot of observations and comments from participants that indicate existence of all three types of constraints.

Physical constraints:

One participant finds the "tree" at the back; she wants to touch the tree. She thinks that she cannot turn as the tree is at her back. Other participant looks very deep down in the virtual world, so she holds HMD by hands; she thinks it will fall off. One more participant notices that she has moved away from the location and then she comes back and then she continues to control her actions. Another participant mentions that "HMD is not too much of the problem but leaning forward and backward with HMD is not comfortable".

Logical constraints:

There are many instances where participants apply logical constraint for touching objects in OSMOSE. Some learned that they cannot touch any of the objects because they went through the objects. Some followed the logical thinking that they cannot touch the objects because OSMOSE is a virtual world. The actual comments are given in the Appendix A.

Cultural constraints:

The participants who are knowledgeable in computer graphics field or visual arts domain tend to know more about the technical limitations of such kind of an immersive environment. Hence, their comments, listed in appendix A, on such conventional limitations are very specific and reflect on their knowledge about this technology.

5.6.6 Dynamism

There are a number of participants who observed the dynamic actions in OSMOSE. In OSMOSE, there are the "white light sources or bugs", as participants named them, and green source code that have dynamism. Two participants tried to follow stream of bugs. One of them wanted to see where they are coming from, located the path, and went against the flow of bugs. Another participant hears sounds which make her feel that there must be some moving objects around. This is one more interesting aspect where the sound can create the effect of dynamism.

User comments about dynamism, given in Appendix A, provide proof of how dynamism affects the understanding of the visualization environment and navigation actions to explore it.

5.6.7 Distinctiveness

In Chapter 4, we had mentioned that we need to study more about this criterion. In "Comprehensibility Study of OSMOSE", we observe some instances where participant gives some reasons why they think some of OSMOSE elements are distinctive. One participant wanted to follow a bug, line of bugs. He later explained that it is because of their color, luminosity and their placement in a line; he wanted to see where they are going. Another participant wanted to look from close how the tree looks like; he said I wanted to see its texture. In the next usability experiment, we continue to study this criterion further.

5.6.8 Emphasis

In OSMOSE, the tree is the prominent and the most attractive object in OSMOSE. Most of the participants (23 out of 25) wanted to go towards the tree. User comments, given in Appendix A, present evidence about this "emphasis" on "the tree". They think that tree is a place or landmark object because of its singularity, central position, brightness.

5.6.9 Legibility

Whenever there is text in the visual representation, it affords reading. Hence, we observe many such attempts of reading different kinds of text in OSMOSE. They speak out loud the words they are reading or react on seeing the words or letters. We give these observations in Appendix A.

5.6.10 Readability

Readability criterion requires visual representation to be easily identifiable, interpretable, inviting and attractive. One way of knowing a person's level of comprehension of any information is by noting down what they are explaining or interpreting about what they understand.

As a first step, we noted down participants' comments while explaining what they were looking at or how they were feeling while experiencing OSMOSE. They expressed their emotions and their interpretations of OSMOSE in their words. These comments are listed in Appendix A. One participant's reaction about OSMOSE theme was the most interesting one. She says:

"There is an ulterior thing that guides us into believing in this world, but the world is not what it seems for us, that's another reality; however, there is hope. So its interesting that it tells us, go find that source of life, go and find that tree, and eventually when you do find the truth which is the tree, then your whole world would become undone and I can spend hours thinking about the meaning of that."

This comment gives us the idea how different people can think and understand the same concept at different levels. Further in analysis, we discuss "readability" in more detail as we try to study different levels of readability and try to categorize participants' comments in different categories.

5.6.11 Symbolism

OSMOSE is a virtual artwork, hence we do not intend to judge the correctness or effectiveness of "symbolism" used in it. During the test session, we just note down the comments made by users where they mention about symbolism or metaphors used in OSMOSE. Three participants tried to see the symbolism in the artwork, but others just saw the actual objects and experienced the navigation in OSMOSE without noticing the symbolism. These three actual comments are included in Appendix A.

5.6.11 Effect of color

We observe that different colors create different moods. We note down participants comments about different colors. They express green to be color of hope and black to be scary and white to be peaceful color. We provide the actual comments in Appendix A. This illustrates how different colors can influence participant's moods and hence the experience. Hence, using the right colors for the intended reaction from the users becomes important factor in creating the right "visual message".

5.6.12 Mapping

Here, we note down users' comments about the mapping of user actions with the corresponding action in OSMOSE. The navigation instructions for OSMOSE are listed down in Appendix A. There are some comments about the comfort level of the current set of user actions. Some express their unhappiness about breathing in to go up in OSMOSE and some suggest use of more body actions for navigation. Their comments are included in Appendix A.

Some observations about participants' actions when they are experiencing OSMOSE are as follows. One participant bends the knees and stretches her hands together to go forward. One participant explores one leaf, by titling the head. One participant turns back, and sees the forest again behind him, so makes the incorrect conclusion that "you have to turn to your back when you want to change the place you are in". One participant points out the tree, makes gestures that something is coming towards her. One more participant points out the locations of code by hand while other says "going down" and puts hands down to indicate "down" direction

All these are some of the natural actions used by users during the OSMOSE experience. These actions can be taken into account along with their questionnaire responses when looking for natural navigational actions.

5.6.13 Responsiveness

Participants comments about responses from OSMOSE are mainly about the navigation actions as the exploration is the main task in this particular visualization environment. They mention when OSMOSE is not responding to their actions and expect it to be responsive all the time. The actual comments are mentioned in Appendix A.

5.6.14 New Criterion from Observations and User Comments

From the comments made by participants, we gathered a set of comments and observations that indicate addition of new criterion under "Organize" principle. These comments are listed below:

- Not much sense of direction, couldn't find out the controls
- There was a point of light with the tail", so you could see what the direction in which they are moving is. So he concluded that they were going in some direction.
- Cannot remember the trace of the journey as I felt lost
- No sense of direction when I lean backwards, it gives the feeling that I am moving up.
- I am looking at stream of lights , looking where they are coming from and where they are going
- Am I going through them or they are coming towards me?
- Tree is coming up (directionality) , everything is going above me, so I must be going below (inference)
- I want to see where the bugs are coming from, so I am going against the flow of bugs

All these comments suggest that participants are looking for some hints about the direction. Hence, we think that "Directionality" should be added as one more characteristic under "Organize" principle. In the next validation study, we again explain whether such directionality is really important in a visualization environment.

Thus, concluding here about the summary of comments and observations, we see that we acquired plenty of information which indicates to that all the proposed criteria actually are relevant and important characteristics of the "visual message" and "visual communication" between visualization environment and the user. And we can identify gap of execution and evaluation wherever participants felt uncomfortable or difficult to perform the intended action or understand the "visual message" communicated to them.

5.7 Descriptive Statistics of Participants Responses to Post Test Questionnaire

As studied in Chapter 2, there are certain perspective and cognitive effects on participants of an immersive environment: presence or feeling of immersion, and effects of depth perception, curiosity to explore, excitement, scary feeling, feeling of "body less" ness. We now present some of the most important descriptive statistics that we gathered to describe the reasons behind participants' particular behaviour. We use their responses for some of the questions in post test questionnaires. Here, at times, we take the help of some of the HMD study results to prove the significance of any particular criterion.

5.7.1 Effect of affordances on presence

65 % participants wanted to touch what you are looking at. This feeling to touch anything comes only when you have some feeling of being in that world. Or the other reason can be the feeling that the object, they are looking at, affords touching.

At the same time, due to some constraints, only 42% actually tried to touch the objects in OSMOSE. They are the physical and logical constraints in their mind that made them aware that OSMOSE is the virtual world. The reasons are evident in the observations and user comments given in Appendix A.

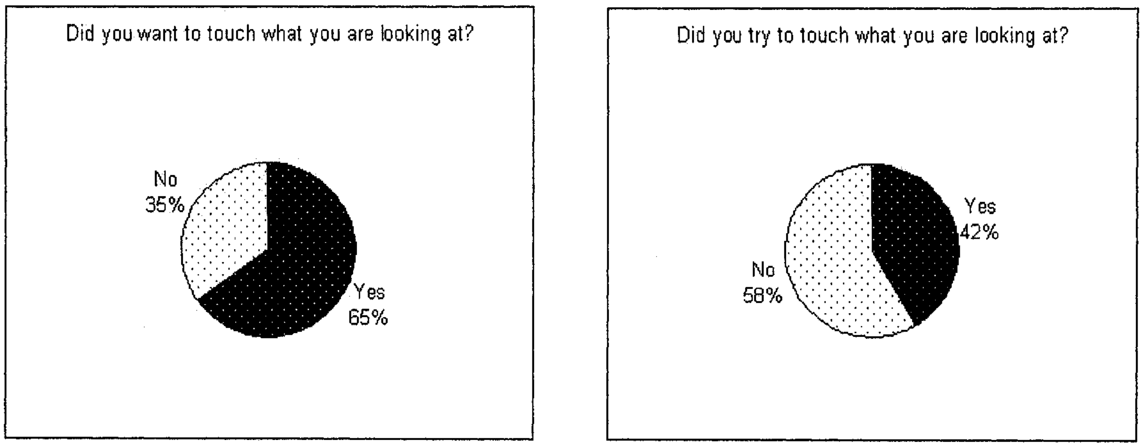


Fig. 5. 3 Effect of affordances on presence

5.7.2 Effect of mapping on user interaction

Due to its immersive nature, OSMOSE gives us the chance to see the direct relationship between the participant actions and the visualization, they see as a result of those actions. We asked participants some questions in post test questionnaire that were closely related to criterion "Mappings". We wanted to review whether the actions they used for OSMOSE were the ones most favoured by the participants.

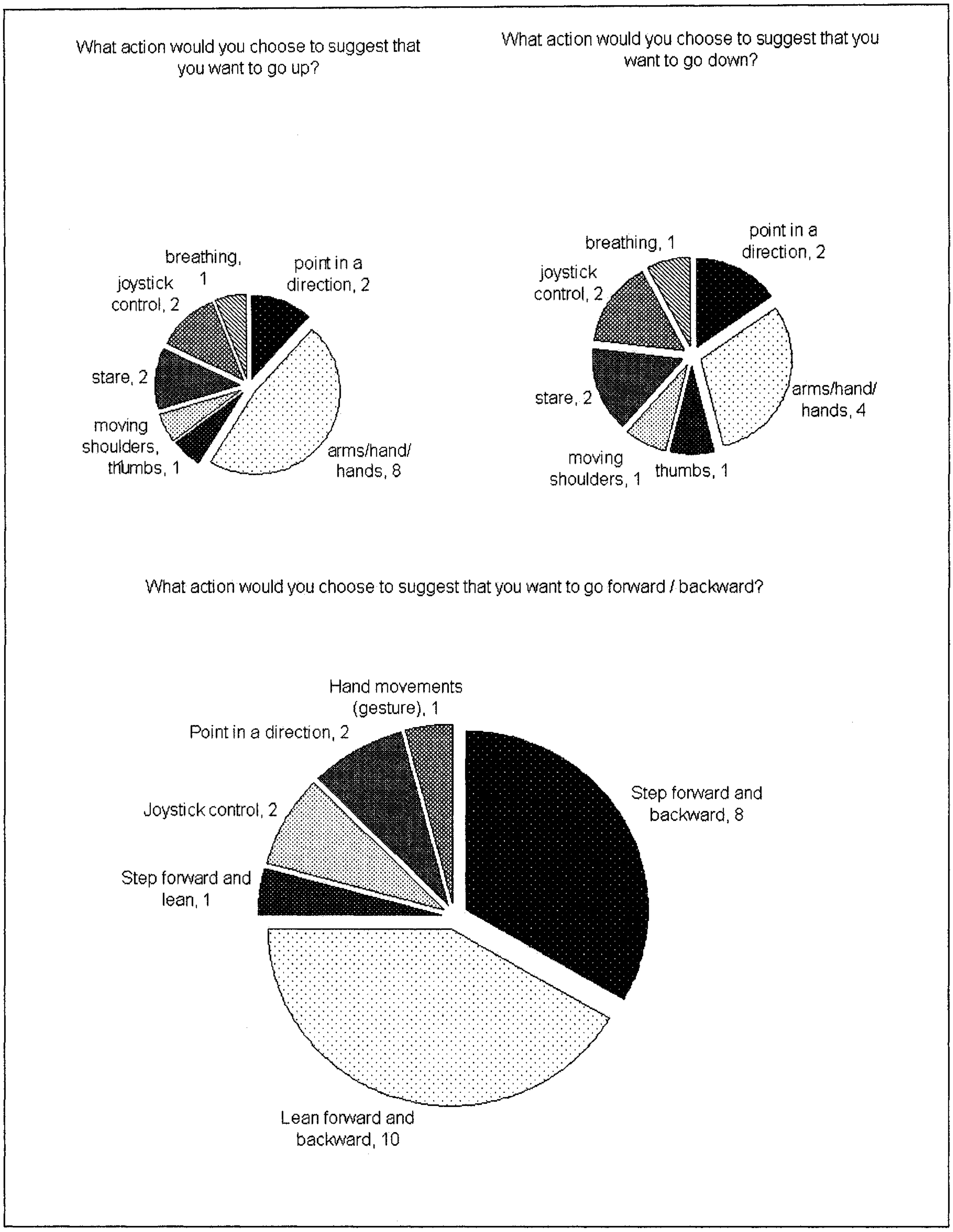


Fig. 5. 4 Effect of mappings on user interaction

In the results, what we found was quite interesting. We found that for "Up and Down" actions, use of arms or one hand or both hands was the most natural and for "forward and backward" there were two clear choices leaning or stepping forward or backward. The question was asked just to find the natural actions that participants thought are easy in an immersive environment.

5.7.3 Effect of navigability on user interaction

According to the artist, there are dozen different "world spaces" (*Immersence* 1995-2005) in OSMOSE, and each "participant" encounters different "world spaces" according to his or her actions. We present two results from HMD study that shows participants ratings for exploration and different navigation actions in OSMOSE.

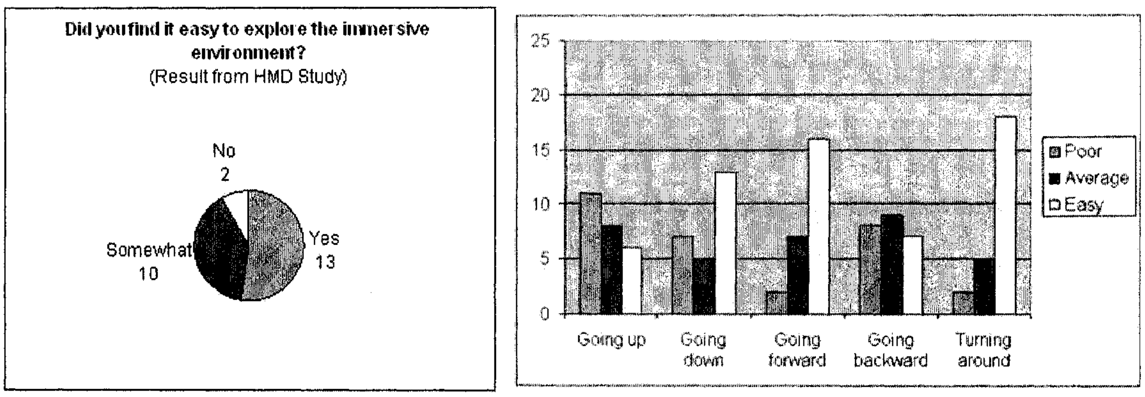


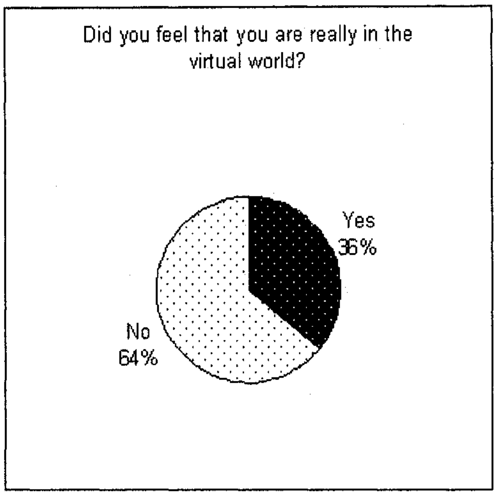
Fig. 5. 5 Rating for navigation actions for OSMOSE

From this result, we see that going down, forward and turning around are the easy actions among all. The problem is evident in going backward as participants have to lean backward wearing the helmet and for going up as they have to breathe in. Here, the aim is to analyze the mappings in an immersive environment and there is no intention to comment on the correctness of current navigation actions designed for OSMOSE as it is an artwork.

5.7.4 Effect of physical constraints on presence

The physical constraints of OSMOSE are to use HMD and vest and use breathing and body movements for interaction.

When participants were asked whether they felt that they are really in the virtual world, 64% responded negative. Even if their behaviour showed some signs of feeling of "presence", 18 out of 25 participants thought that HMD and 14 out of 25 thought breathing made them aware of the outside real world.



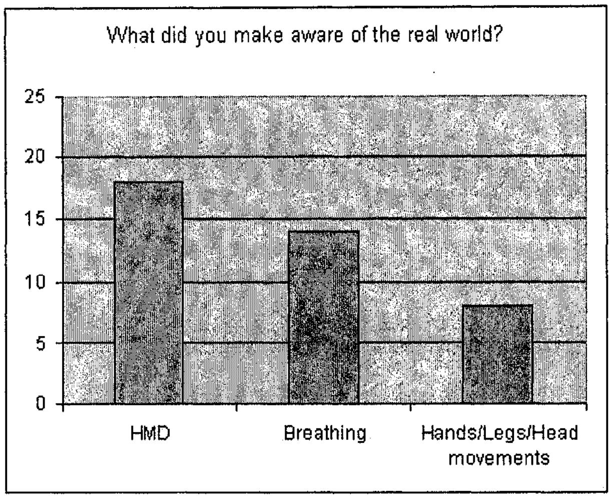


Fig. 5. 6 Effect of Physical Constraints on Presence

5.7.5 Effect of responsiveness on user interaction

When asked about the responsiveness of OSMOSE for participants' actions, we receive following result from HMD study:

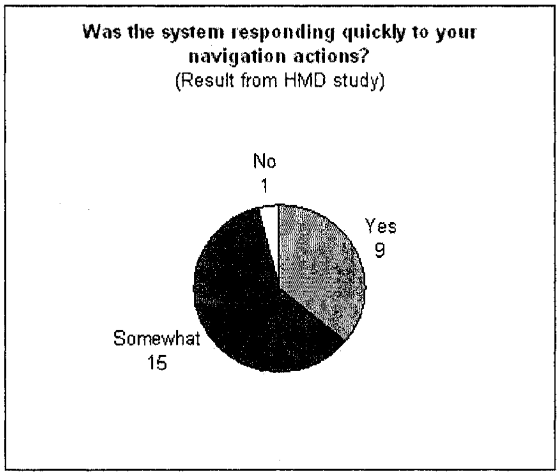


Fig. 5. 7 Effect of Responsiveness on User Interaction

5.7.6 Effect of readability on user comprehension

The main criterion that deals with the participant's comprehension of the visualization environment is "Readability". Aaron Marcus suggests four attributes for "effective visual communication". It should be inviting, attractive, identifiable and interpretable (Marcus 1995). We look at each of these attributes in detail. First, we present two results from HMD study that talk about invitingness and attractiveness of OSMOSE.

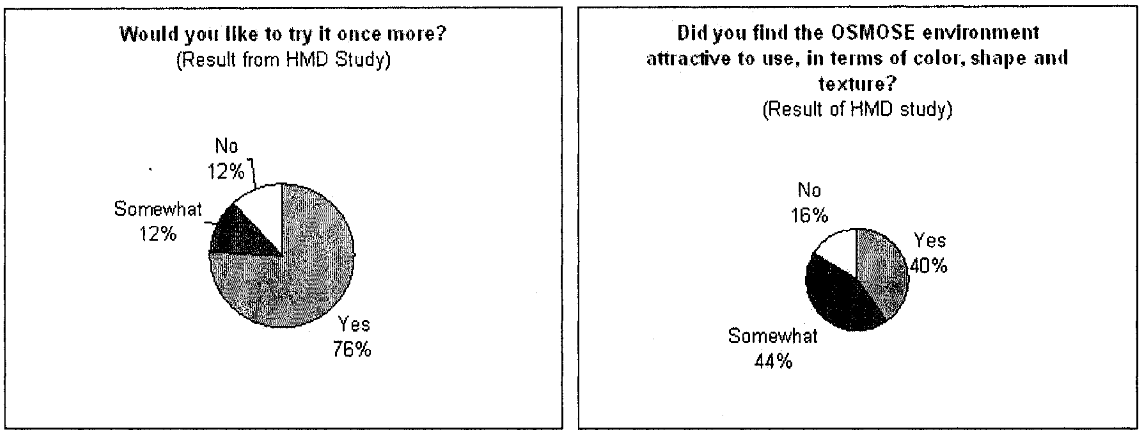


Fig. 5. 8 Results about Invitingness and Attractiveness of OSMOSE

Majority of participants, that is 76%, feel that they definitely want to try OSMOSE again. But, in terms of attractiveness, the response is mixed.

When asked whether they understood what's going on in the environment, the response shows that only 16% of the participants did not understand what is going on in OSMOSE. 64% participants are positive, and 20% are somewhat sure that they understood.

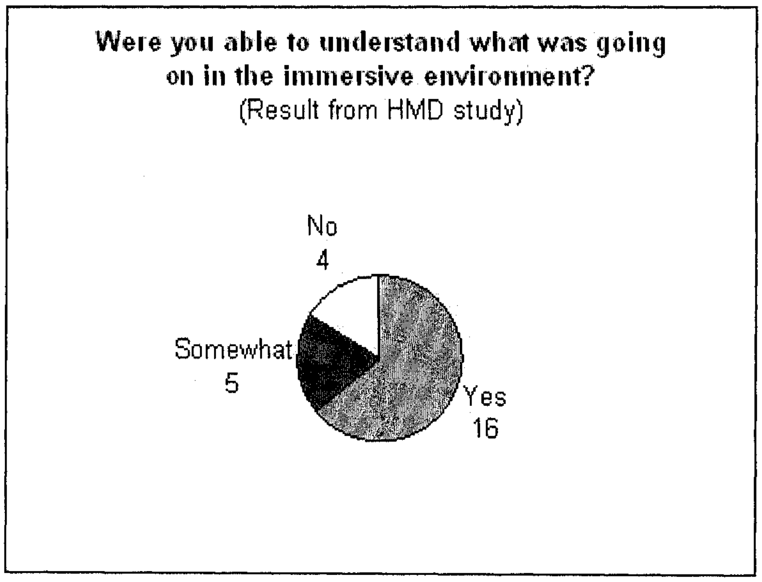


Fig. 5. 9 Results about Understanding OSMOSE

To know exactly what they understood in OSMOSE, in the previous section, we looked at the comments they made while experiencing OSMOSE. Further, to see how easy OSMOSE is to understand and interpret, we asked users what objects they saw and what colors they remember from OSMOSE. This way they try to interpret what they saw and respond accordingly.

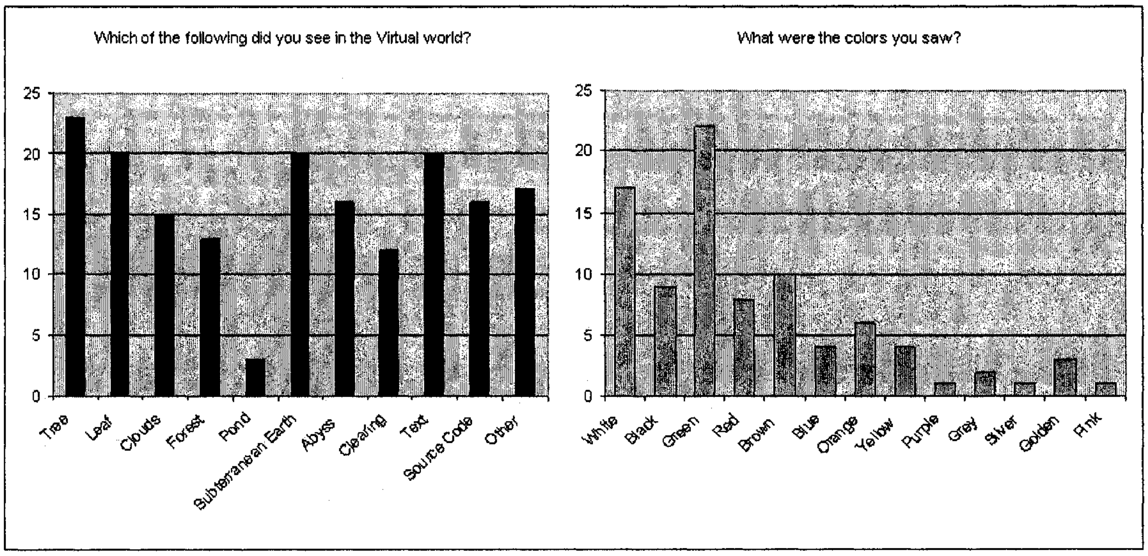


Fig. 5. 10 Results about objects and colors seen in OSMOSE

In the list of objects, "pond" looks difficult to see or recognize and the prominent colors observed in OSMOSE are green, white, brown, black and red.

By considering all the responses above and users comments regarding all the criteria, we try to summarize user's readability levels of OSMOSE. We observe that there are roughly three levels of comprehension in OSMOSE.

1. A few participants cannot navigate successfully or correctly in OSMOSE. As exploration is the main task in OSMOSE, they cannot get "the feel of OSMOSE" and hence, they do not understand what is going on in OSMOSE.

2. Many participants manage to explore the world by navigation actions. They enjoy different "world spaces" (*Immersence* 1995-2005) of OSMOSE by looking, going towards and through them. Overall they enjoy being in an imaginary world.

3. A few participants experienced OSMOSE from an artistic point of view, they try to see metaphors in what they are looking at. Some explore OSMOSE more than others, but mainly they enjoy OSMOSE as an artwork, not just as an imaginary world.

These different understanding levels are caused by different factors. We see that, what the participants comprehend depends on them. Participants who are artistic in nature, they try to look at OSMOSE from artistic point of view and try to find metaphors. Others just enjoy the immersive experience.

Their navigation patterns are also based on participant's personality. Some participants do not try to control their position. They just take a back seat and observe the environment. Some users want control over their navigation and choose their direction in which they want to go and look. They always want to go some where and reach somewhere fast. As a result, they explore more and do more innovative exploration. But again what they understand from this exploration is a personality issue. Some participants balance the exploration and observation tasks and enjoy the artwork.

These statistics describe some of the most important results from our study. There are some more statistics that we collected and were not directly related to the proposed set of criteria. They provide insight onto some more cognitive effects like attention, enjoyment and remembering OSMOSE elements. These statistics are included in Appendix A.

5.8 Concluding Remarks

In this chapter, we have presented results from our usability experiment - "Comprehensibility Study of OSMOSE". The main goal was to study different aspects of visual communication between immersive visualization environment and the user. This experiment gave us a large amount of information about this visual communication. We analyzed the test sessions and interview sessions to collect evidence for the validation of comprehension criteria we presented in Chapter 4.

In this study, we gain very important knowledge about "Mappings" in an immersive environment, and effects of "Readability" on the "visual message". We also observe the evidence of "Navigability", "Dynamism", "Constraints", "Distinctiveness" and "Emphasis" of the "visual message" on exploration task in OSMOSE. In our opinion, a very important discovery is the new criterion "Directionality" that we realized from user comments. In the next study, we validate its importance again.

We know that OSMOSE is an artwork and it is not created by confining to any rules of effective visual communication. We do not intend to assess OSMOSE for its artistic importance and significance. The opportunity to use such a distinguished immersive environment is very rare. We consider ourselves fortunate to use this immersive environment as a tool to understand user's interaction and user's comprehension process using such an immersive visualization environment. We request that all the comments and participants' reactions be regarded from a learning perspective only.

Chapter 6: CASE STUDY II – ADN VIEWER

This chapter presents second case study to understand the visual communication process between visualization environment and its users. This second usability study is conducted on the three-dimensional DNA visualization software, "ADN-Viewer".

This case study presents the opportunity to understand the information visualization environment and user's interaction with it, as textual sequences of DNA are presented in a 3D form. In this study, we plan to ask criteria specific questions and note down all the related observations during the test sessions. Thus, this case study provides more appropriate visualization environment to understand whether its designer's "communication" intentions about DNA visualization are met by information "seeking" intention by its users.

6.1 DNA Visualization Environment: ADN-Viewer

"ADN-Viewer" is a software tool for 3D modeling and stereoscopic visualization focused on the virtual exploration and the bioinformatics analysis of genomic sequences (Hérisson et al. 2005). This software is developed by LIMSI Bioinformatics team, University of Paris-Sud XI, at Orsay. Opportunity to conduct such a usability study was possible because of the visiting associate professor Dr. Rachid Gherbi from LIMSI lab, who is also one of the developers of ADN-Viewer.

6.2 Developer's description about ADN-Viewer

According to developers of ADN-Viewer, there are two main intentions behind presenting the visualizations:

1. Virtual exploration
2. Bioinformatics analysis of genomic sequences

According to the developers of ADN-Viewer (Hérisson et al. 2005), the 3D representation and visualization of DNA molecule and interacting with it make it possible to have a global point of view of the sequence, in opposition with the textual format. According to the developers, this brings a new vision and an original approach suitable to launch new bioinformatics studies for the analysis of the genome. Besides, in order to obtain a friendly powerful interactive visualization, various representations are necessary in order to adapt the visualization according to different analysis cases. All these requirements are met with ADN-Viewer. According to the developers, to analyze spatial relations between genomic elements, it is possible to display the genes of chromosomes.

6.3 Using ADN-Viewer

In the LIMSI laboratory, where the immersive environment for ADN-Viewer is available, the "visual presentation" is presented on two panoramic screens, user has to wear the shutter glasses for depth perception and user interaction with ADN-Viewer is achieved by various physical actions like, pointing towards a direction, looking around, saying words and staring in one direction. But, here, in Concordia University, as this immersive environment setup wasn't available, ADN-Viewer was used as normal desktop software where user interaction is achieved using keyboard and mouse; "visual presentation" was presented with two options: on a Monitor screen or on the wall projection. The simpler, low-cost glasses were provided for stereoscopic vision. Its use was optional.

6.4 Comprehensibility Study of ADN-Viewer

The Study of ADN-Viewer is divided in two parts. First part is the assessment of NCBI website which is the focus of research for another team member. The second part is the "Comprehensibility Study of ADN-Viewer". It involves performing two tasks using ADN-Viewer.

6.4.1 Goal

Goal of this ADN-Viewer study is to validate whether the set of proposed criteria can characterize the comprehension gap between visualization environment and its user. As in the "Comprehensibility Study of OSMOSE", we try to understand the visual communication between ADN-Viewer and its users by noting down the observations and by asking them questions after each task and after the test session is over.

6.4.2 Constraints

The main constraint in this study is the absence of the immersive environment setup for ADN-Viewer. This restricts the communication between ADN-Viewer and its user to the normal set of interaction devices such as monitor for viewing and keyboard and mouse for user interaction. The study of ADN-Viewer with the immersive environment remains as future work.

Number of participants remains another challenging problem in this study. Finding the participants who are in the field of bioinformatics or related domains and the ones who are interested in viewing the 3D structures of DNA sequences proved to be a difficult task. We managed to invite 11 participants for this study though we are aware of the fact that more number of participants will strengthen the findings.

6.4.3 Usability testing process

The testing process used in ADN-Viewer study is same as the one used in previous study "Comprehensibility Study of OSMOSE". It is included in appendix A.

6.4.4 Tasks

While selecting the tasks for "ADN-Viewer study", we consulted Dr. Rachid Gherbi and chose two tasks which, according to Dr. Gherbi, are the ones for which ADN-Viewer is the most useful. We decided to find out whether developer's intentions are right and how useful ADN-Viewer actually is in assisting users for these tasks.

3D Sequence Grouping Task: As a First task, we ask the participant to open a number of sequences using "File Open" dialog and group them according to the similarity in their 3D structure. Dr. Gherbi anticipated that ADN-Viewer helps making such grouping of sequences. Dr. Gherbi mentions that it is a typical task for ADN-Viewer users because, after doing such grouping task, users can know which are the sequences with similar structures and they can conduct certain laboratory experiments on these sets of sequences to find out more commonality between them.

3D Structural Analysis Task: Second task wants the participants to open a particular DNA sequence and then find the pair of gene names which are actually far in the textual sequence but are close to each other in 3D space. Dr. Gherbi mentions that such closeness is visible to the user only because of the visualization of 3D structures of the DNA sequences in ADN-Viewer. By looking at such close structures, participants can investigate whether this pair of genes has any effect on each other. The document that explains the goal and instructions for each task to the participant is included as part of Appendix B.

6.4.5 Participants

This case study differs from the first one in one more respect. The users for "ADN-Viewer" are a very specific group of people compared to those for OSMOSE. OSMOSE is a virtual artwork that any person can explore and experience, but ADN-Viewer has a specific purpose for its use. Hence, participants who some minimal level of expertise in analyzing DNA sequences are invited. The user evaluation form for these participants is included in appendix B. Now, the questions about each participant's background touch different aspect of user's expertise about DNA structure analysis. To categorize the 11 participants as novice, intermediate and expert users, there is no standard method; hence, we use following simple procedure.

First, gather the background information about each participant. It is done by asking questions about user profile, bioinformatics and biology knowledge, computer related experience and finally, application experience. All the questions in these sections are yes/ no or multiple choice questions. This user evaluation form is the adapted version from the master's thesis of one of our group members. (Javahery 2003) To count responses for each question, the score sheet is decided for each question in the user evaluation form as given in Table 6.1.

Table 6. 1 Scoring Scheme for User Evaluation Questions

Question	Options	Score
Highest Level of education	B.Sc.	1
	M.Sc.	2
	Ph.D.	3
Current Position or employment	Master Student	1
	PhD Student	2
	Professor or Scientist	3
Number of graduate bioinformatics courses	None	0
	1-2	1
	>2	2
Knowledge of biological sciences	Basic	1
	Intermediate	2
	Advanced	3
Years of working in bioinformatics or molecular biology	Not applicable	0
	< 1 years	1
	1-3 years	2
	> 3 years	3
Knowledge of information technology and computer science	Basic	1
	Intermediate	2
	Expert	3
Experience with bioinformatics tools	Basic	1
	Intermediate	2
	Advanced	3
Experience with a virtual or 3D environment	No	0
	Yes	1
Used any 3D bioinformatics visualization tools	No	0
	Yes	1 * (number of tools used)
Worked with textual sequences	No	0

	Yes	1
Is 3D structure of biological sequences important to you?	No	0
	Yes	1
If relevant, what kind of 3D structures have you worked with?	None	0
	Software or physical model	1
	Software and physical model	2

Now, for every participant, responses for all user evaluation questions are replaced by their corresponding score values. The final score for each participant is calculated by summing up these score values. This ensures that each response contributes towards deciding the user expertise. This score sheet for every participant is included in appendix B. This final score for all 11 participants is plotted in the figure below.

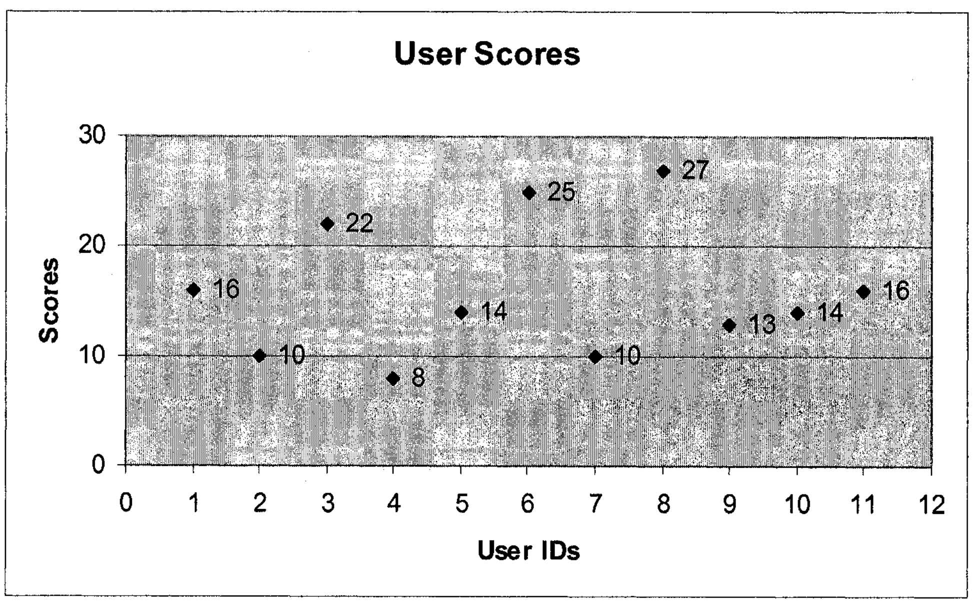


Fig. 6. 1 Scores for ADN-Viewer Participants

These final scores range between 8 and 27. Hence, this sample space is divided in three equal ranges and we define 3 user levels for each range: Novice user (Final Score: 0-10), Intermediate user (Final Score: 11-20) and expert user (Final Score: 21-30). By sorting the final scores for 11 participants, we categorize them as 3 novice users, 5 intermediate and 3 expert users.

This procedure is necessary in this study as the user expertise plays major role in analyzing the questionnaire responses. While summarizing the responses, we decide to give different importance to different users' responses. Expert user's responses hold more weight than the novice users' responses. For this decision also, we follow a simple way of deciding different weights: expert user's responses hold the weight 3, intermediate user's responses hold weight 2 and novice user's responses hold the weight 1.

After describing this scoring strategy, now in the next section, we present the first level of analysis where we understand this study from the perspective of visual communication.

6.5 Understanding Visual Communication between ADN-Viewer and "Model Human Processor"

As in the first study, we first try to model the ADN-Viewer and participant's side in the form of a model. We use "Model Human Processor" to model participant's information processing capabilities and we model ADN Viewer as an interactive visualization environment. Its user interface captures the user actions that are originated by processing the perceived information, ADN-Viewer software then processes the user actions and changes the view shown to the user. This is the response that ADN-Viewer gives to user's mouse or keyboard actions. Depending on this view, user decides next action depending on what he/she understood about the 3D structure of DNA sequence. This whole process can be summarized in the following diagram.

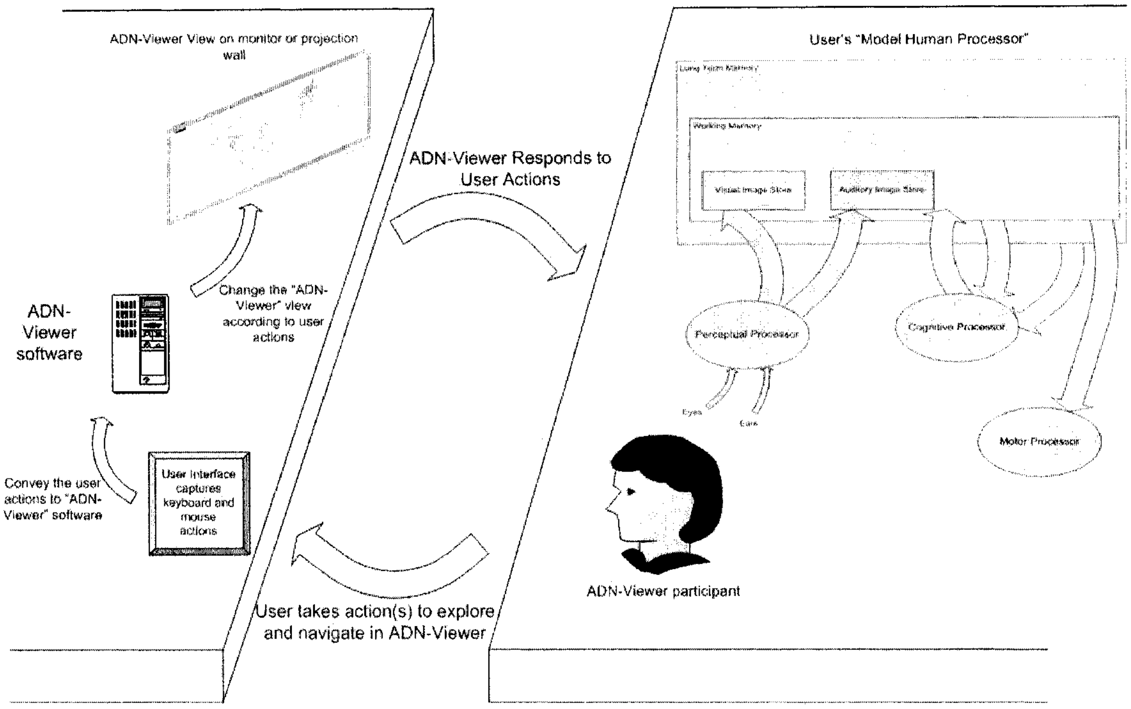


Fig. 6. 2 Visual Communication Between ADN-Viewer and User

Thus, we can see that in this scenario, there is a two-way visual communication process that exists between ADN-Viewer and its user. In the next section, now, we summarize the observations about this two-way communication.

6.6 Summary of Observations

There are some interesting observations during the test sessions that we present in this section. These observations are categorized according to their relevance to the proposed set of criteria.

6.6.1 Observations about Clustering

First task in this study was about grouping a set of sequences. As the ADN-Viewer helps mainly in viewing the 3D structure, this task was focused towards participant's grouping activity depending on the 3D structure. We asked the participants what criteria they had used to group the sequences.

Some participants tried to remove the depth factor from this structure as far as possible (by making them flat) and some kept rotating them to see the 3D structure in different angles before grouping them. A few used glasses to see them in stereoscopic vision. Actual responses according to their different expertise levels are listed in Appendix B.

6.6.2 Desire for Affordances

Participants desired to see the "perceived affordances" to the mouse pointer. Some suggested showing a hand, grabbing the sequence, when he/she clicks the mouse button for translation or rotation. Sometimes, it was observed that mouse pointer was too small to be visible to the participant and participant searched for mouse position on the screen. When asked whether there is anything that you did not like about ADN-Viewer?" One of the responses was "I couldn't see the cursor on screen". It is desired by the participants that mouse pointer should always be more visible on the screen when they are interacting with the DNA sequence.

6.6.3 Use of conventions as positive transfer effect

Though we didn't ask any questions regarding affordances, we noted some observations about such perceived affordances. ADN-Viewer uses standard user interaction devices such as keyboard and mouse. Hence, many conventions related to mouse were followed by participants. This is evident from their responses for the natural mouse actions for different navigation actions. This response is summarized in the Descriptive analysis section.

6.6.4 Distinctiveness and emphasis due to effect of colors

The study of colors and its effective use in ADN-Viewer makes the genes appear distinctive. According to (Saint-Martin 1987), when yellow and violet tints are put side by side on a black background, the luminous yellow appears to advance distinctly into the foreground while the violet recedes in depth in the dark ground. In ADN-Viewer, 3D DNA structure trajectory is displayed on a black background with yellow color for genes and violet for intergenic regions. It is a very basic fact that in a DNA sequence, the genes are of more importance and should be emphasized. Hence, ADN-Viewer is observed to put more emphasis on the genes in a sequence while intergenic regions colored in violet recede in depth and do not distract user's attention from the genes.

6.6.5 Symbolism

The tasks for this study are based on one particular "visual representation" of DNA sequence: a trajectory of DNA sequence was visualized using a thin line in 3D space. Some participants didn't understand this "visual representation" just by looking at it. After the coaching session, when the working of ADN Viewer was explained to them, they were satisfied with it. In general, they expected to see more traditional representation of DNA sequence where the A, T, C, G nucleotides are displayed in their 3D structure. ADN-Viewer has the capability to present different DNA representations, though the scope for this study was limited to one representation.

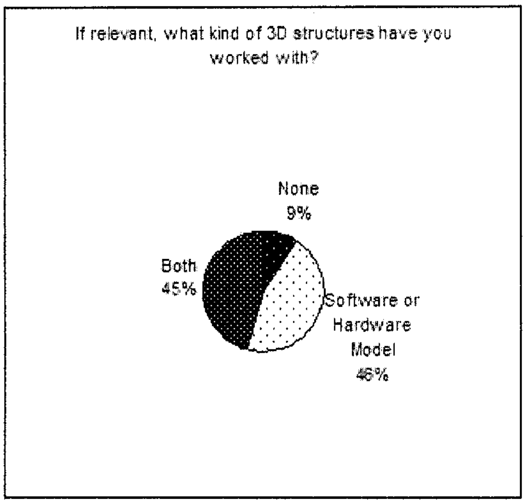
In the next section, we present the descriptive statistics of participants' responses according to their relevance to certain criterion.

6.7 Descriptive statistics of participants' responses to questionnaires

In this study, questions related to different criteria were asked in the form of three questionnaires. While analyzing the responses, we choose question (s) according to their relevance to a specific criterion. For scoring, we assign specific weight to each user response according to his/her expertise level. The weights are 1, 2 and 3 for novice, intermediate and expert users respectively. These values are then substituted for each response given by each participant. We sum up the score for each option for each question. As we have three novices, five intermediate and three expert users, the maximum score that any question can get is 22. Subsequently, all the graphs in the descriptive analysis section have score range from 0 to 22. The detailed analysis is given in detail in Appendix B. Here, we present some of the more interesting results from this analysis.

6.7.1 Responses about Real world consistency

During the user evaluation before the test began, we asked the participants whether they have worked with any DNA 3D structures before; we received positive responses where, except one, all the participants have seen either software or physical models. But, after participants finished task 2, when we asked them whether this 3D DNA representation is consistent with what you have seen before, we received surprisingly indecisive result as shown in Figure 6.3.



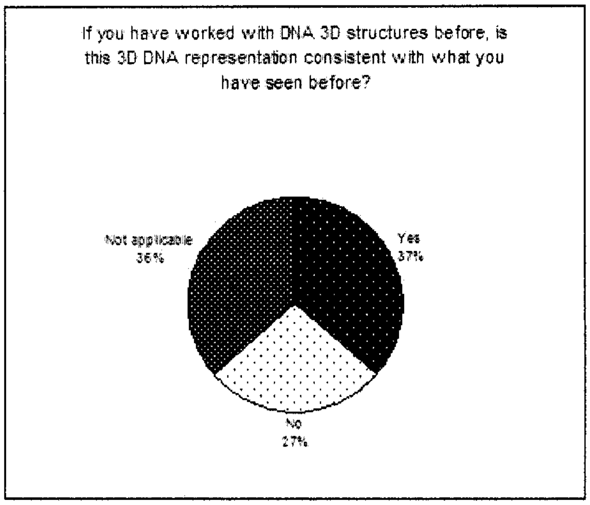


Fig. 6. 3 Responses about Real World Consistency

This needs further investigation during future studies conducted on ADN-Viewer. There is one possibility for such response. For this study, we selected a visual representation showing DNA trajectory instead of DNA sequence representation with A, C, T, G nucleotides.

6.7.2 Navigability in ADN-Viewer

Exploring DNA sequence from all directions is a major intention behind using any molecular visualization software. Hence, in the post test questionnaire, we asked how comfortable was it to explore a DNA sequence in different directions and we received following response.

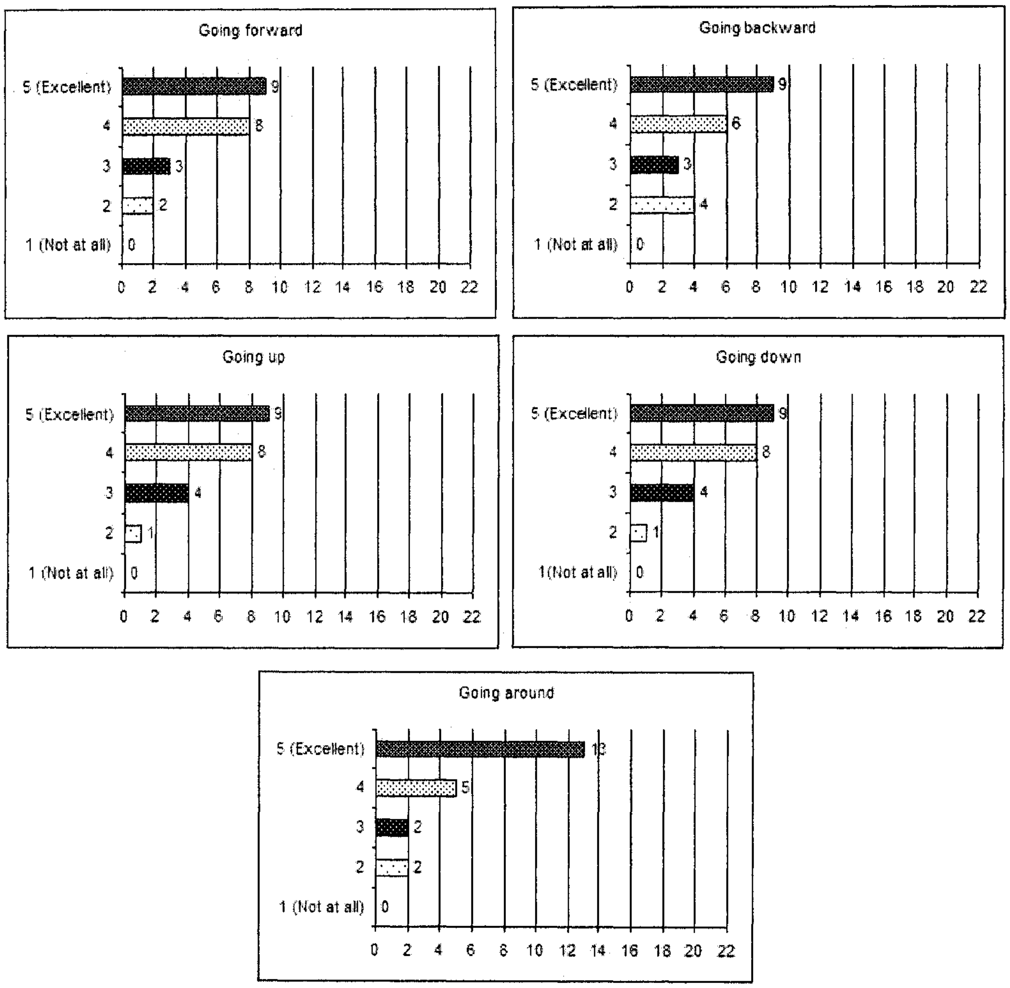


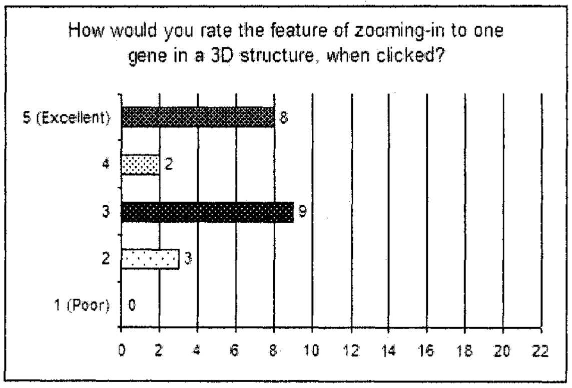
Fig. 6. 4 Responses about Navigation Actions in ADN-Viewer

ADN-Viewer fairs well in navigation action as it follows the conventional navigation mouse actions. With some exception, the mouse actions are not too different than user's conventions.

6.7.3 Dynamism in ADN-Viewer

In ADN-Viewer, when participant clicks on one gene, the visualization environment takes the control and creates the animation effect of zooming onto the selected gene. We asked some questions to the participants to rate this feature and to rate its usefulness.

The descriptive summary of the responses for these questions is given in the Figure 6.5. Though majority of the participants thought that such zooming onto one gene is essential, there was a strong negative response on the feature's performance itself.



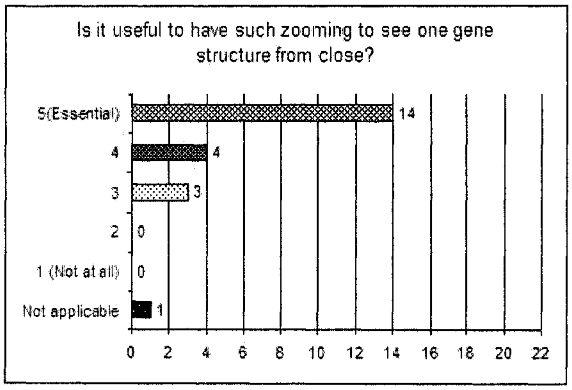


Fig. 6. 5 Responses about Dynamism in ADN-Viewer

One expert and intermediate participant and three novice participants asserted that this feature is excellent. But this response is opposed by two expert and three intermediate participants. They explain the reason behind giving such low ratings. The reasons are as following:

- (It is) confusing because it rotated the sequence
- (It) looks nice but gets you lost in sequence

6.7.4 Responses on effect of Depth Perception

In this study, the help to improve depth perception was in the form of low-cost glasses. When asked about observing DNA structure with stereoscopic view, the participants responded positively. But, when asked how frequently you would like to use glasses, the most favorite response was to switch between the normal and stereoscopic views.

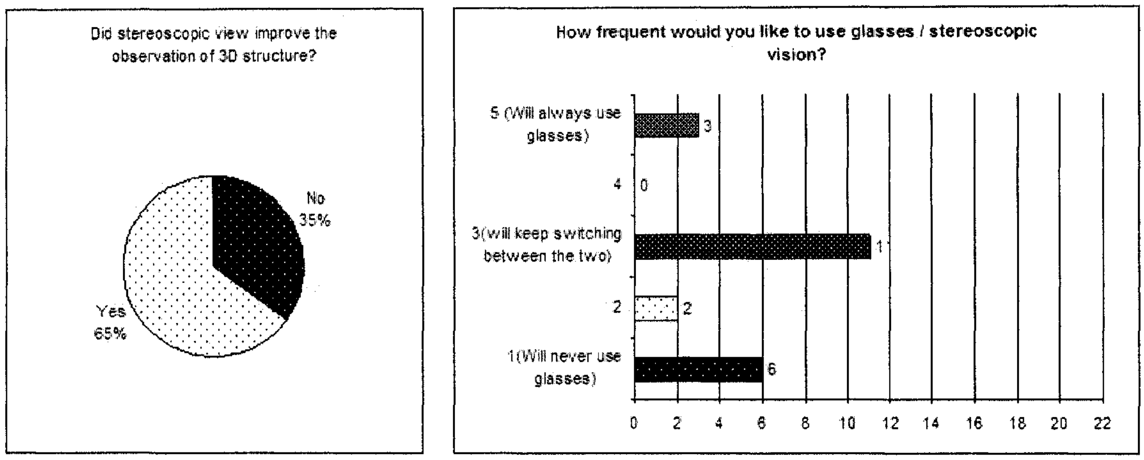
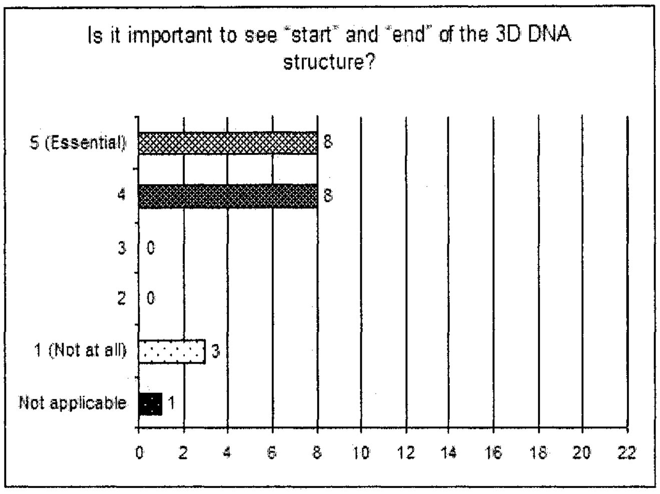


Fig. 6. 6 Depth Perception in ADN-Viewer

This indicates that because of some reason, participants don't want to keep the stereoscopic view all the time during their DNA structure analysis tasks. It indicates need for careful further investigation during future studies on ADN-Viewer where shutter glasses are provided to the participants.

6.7.5 Responses on Directionality

Regarding this new criterion of Directionality found in the first case study, "Comprehensibility Study of OSMOSE", we noted some observations. In ADN-Viewer, start and end of a DNA sequence are indicated with the words "start" and "end" in the 3D visual presentation. It is necessary to find out whether the participants noticed it, all the participants without any exception responded positively. Now, as a next level, we asked whether it is important to show such direction and is it sufficient to have this "start" and "end" words to indicate the directions. We received following responses.



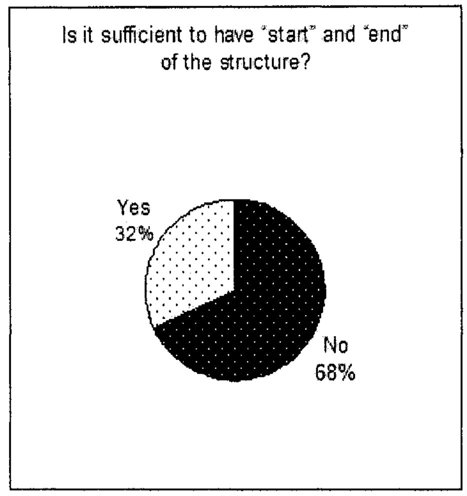


Fig. 6. 7 Importance and Sufficiency of Directionality in ADN-Viewer

On the sufficiency for directionality, we collected some interesting suggestions for showing direction in a 3D DNA structure. User comments are listed down in Appendix B, but in summary, it indicates that users want to see an arrow or their familiar terms like 3' and 5' that shows the direction more easily.

6.7.6 Responses on Simplicity

Simplicity is a tricky criterion to investigate. In ADN-Viewer, the intention is to explore 3D DNA structure; hence, the whole emphasis should be on this 3D structure. We asked the participants whether anything unnecessary was noticed by them.

Though, not the majority, there was one suggestion about the option to remove "File Explorer" from the scene. In the future studies on ADN-Viewer, any similar suggestions should be observed.

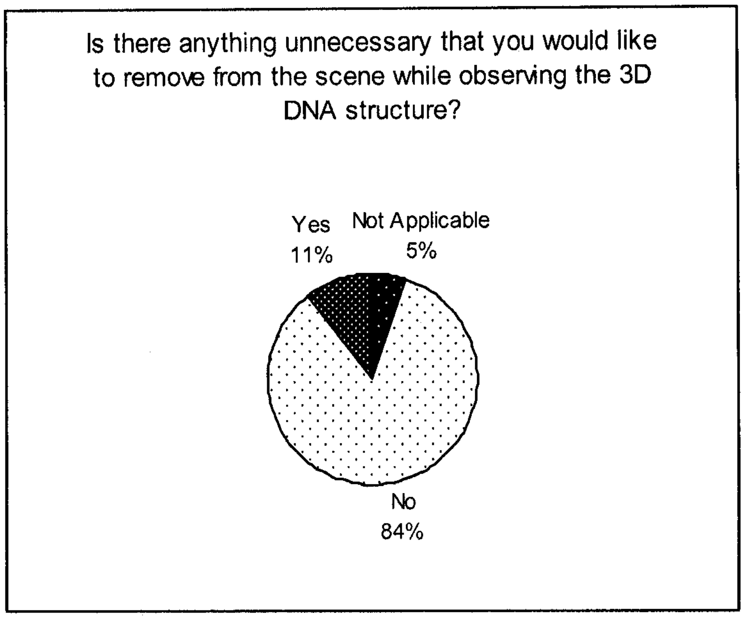


Fig. 6. 8 Simplicity in ADN-Viewer

6.7.7 Intuitiveness in ADN-Viewer

During the ADN-Viewer test sessions, we observed the fact that file explorer and the workspace where user can explore the 3D DNA structure was intuitive to the user. But, to gain more knowledge about their intuitive interaction tasks, after the test session, we asked them to mention the obvious things they would like to do to observe any DNA sequence. We gave them a number of options and received following response.

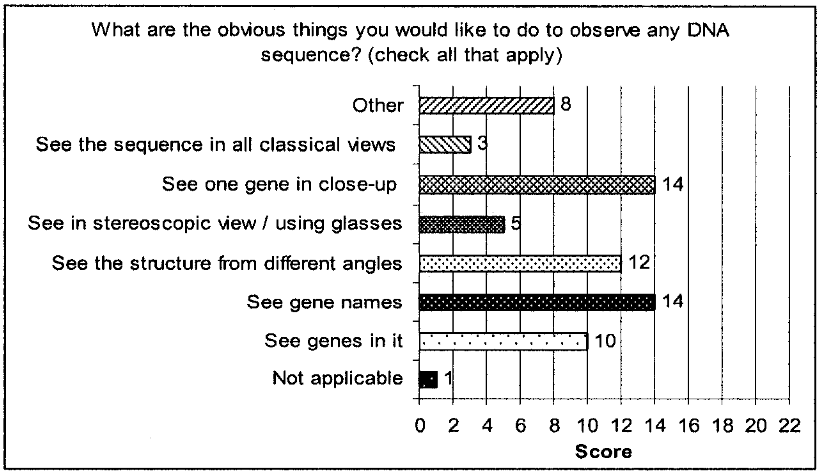


Fig. 6. 9 Intuitive Tasks in ADN-Viewer

The most intuitive tasks are to see gene names and see one gene in close-up. There is one surprising observation that the task "See genes in it" receives low score of 10. It is possible that seeing genes in a sequence is not considered as a separate task by the participants. Validation of this possibility remains open for further investigation in future studies on ADN-Viewer. In "Other" option, participants mentioned following tasks:

- Information about its protein interactions,
- To see in what angles you are looking at the structure,
- Zoom in and out, rotate, move etc.
- If that gene is attached, how that would affect the neighbourhood of that gene? (Which one is close-by?)

6.7.8 Legibility in ADN-Viewer

There are some issues related to the gene names shown along with the 3D structure of a DNA sequence. There is an option to turn ON/OFF the gene names. When enabled, the gene names are shown along with the 3D structure. We asked the participants to rate this feature and enquired whether it is important to see all the gene names at the same time.

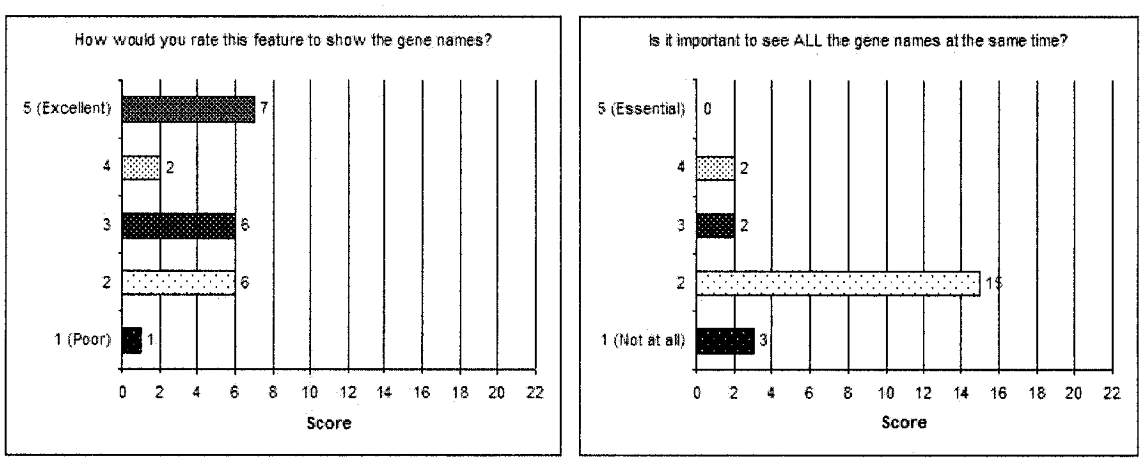


Fig. 6. 10 Responses about Legibility in ADN-Viewer

This feature of showing gene names is appreciated by one expert and two intermediate participants with one participant expressing that the feature is excellent but with the use of rotation. But, two experts, two intermediate and three novice participants rated this feature as 2 and 3. Also, when asked whether it is important to see all the gene names at the same time, we received largely negative response. To find out whether legibility problem is one of the reasons behind this feature's performance, we asked one more question about legibility and received the following mixed response.

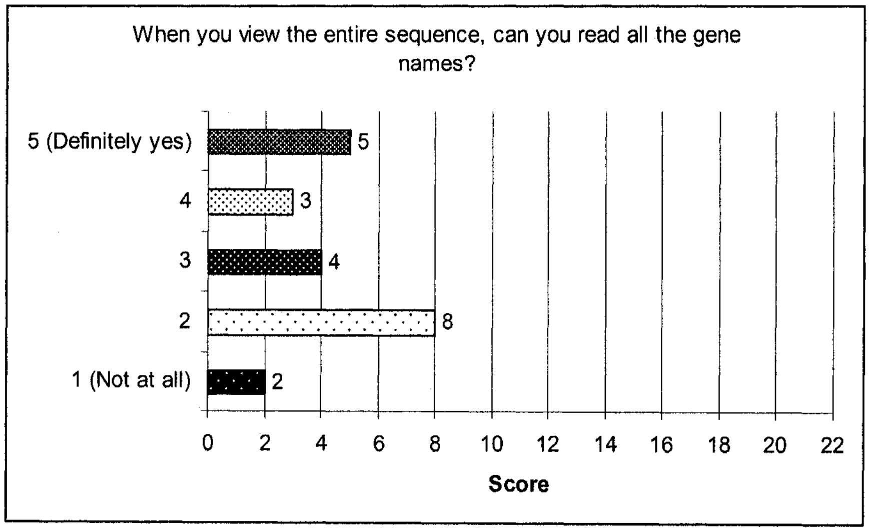


Fig. 6. 11 Evidence of Legibility Problem in ADN-Viewer

All the intermediate participants mentioned that they cannot see all the gene names. One of the participants mentioned the reason why: "It depends on zoom". When participant zooms out and enables the gene names, all the gene names look cluttered together. One of the responses for the question "Is there anything that you did not like about ADN-Viewer?" was as follows: "Gene names are cluttered, one suggestion is to see names that are closer." Two experts, one intermediate and one novice participant also mentioned that they didn't like names in ADN-Viewer.

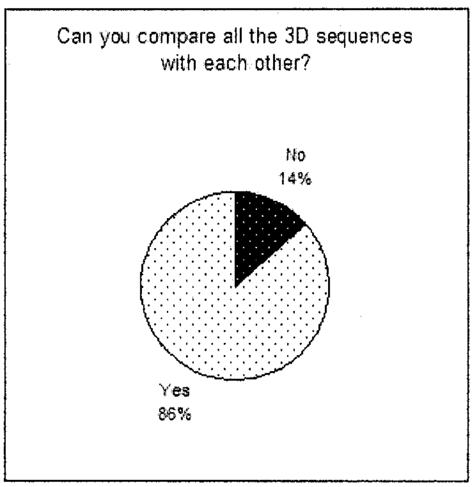
So, legibility problem in ADN-Viewer is about the gene names. Some of the suggestions for improvement are:

1. Allow the user to select an area to see the gene names
2. Show the gene names that are closer in 3D space

6.7.9 Readability in ADN-Viewer

We have proposed that readability can be understood by user's actions. Hence, while summarizing the participants' responses on both the tasks, we observe user's performance in both the tasks.

In this study, task 1 is about comparing a group of sequences for their similarity in 3D structure. Hence, for the correct readability, we wanted to find out whether they can see and compare the sequences as expected from them. First, we asked whether they can see all the sequences together. We received 100% positive response. One novice user faced some interaction problem though and mentioned that "I could see them but it wasn't easy to manage or move them on screen ".



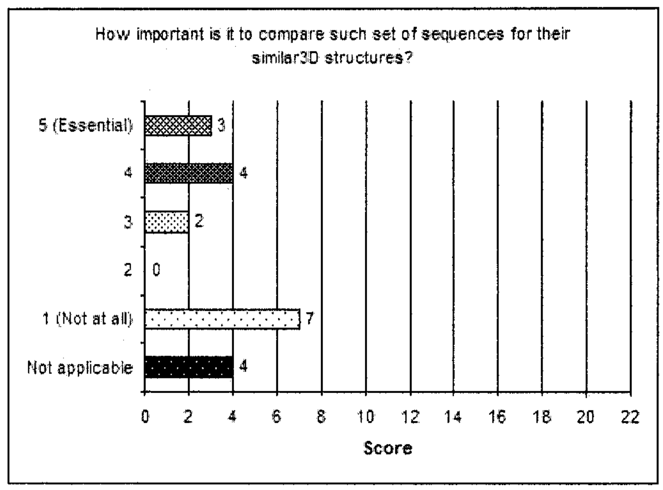


Fig. 6. 12 User Ratings for Sequence Grouping Task

We then asked whether they can compare these sequences for their similarity of 3D structure. The response was positive again with some exception. One participant mentioned that "after I grouped them, they were on top of each other in their respective groups". About the importance of such comparison task, the response was mixed and the reason was the context. Two experts thought that it was not at all important to compare a number of DNA sequences for their similarity in 3D structure, whereas another expert user mentioned that it is essential to compare such sequences. We propose that usefulness of such task depends on what kind of analysis the participants wish to do on DNA sequences.

Task 2 was about identifying a pair of genes in a particular DNA sequence. All eleven participants were successful in finding at least one pair of genes which is close in 3D space but far in textual sequence. The response was as given in the following graph.

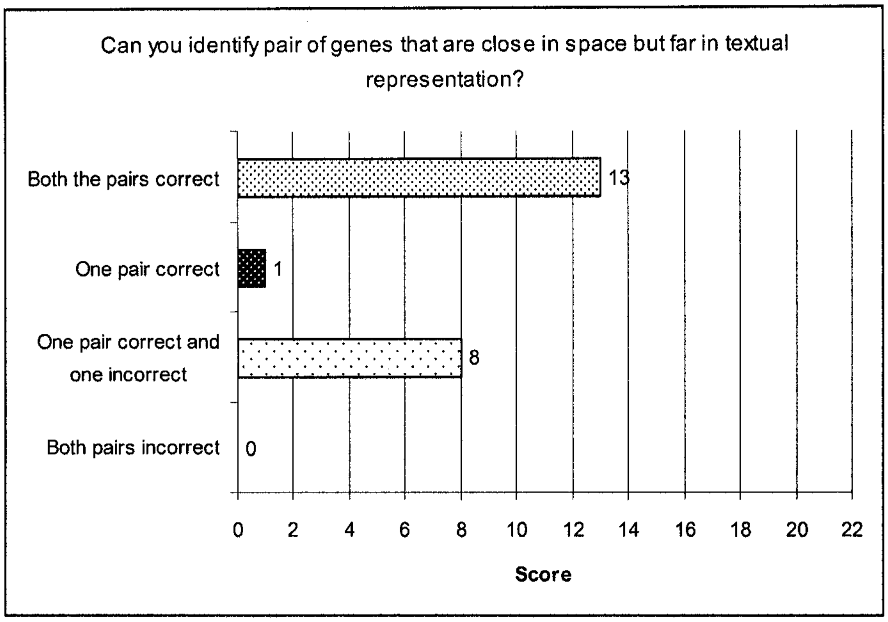


Fig. 6. 13 User Performance for Sequence Analysis Task

One expert, two intermediate and one novice user identified one correct and one incorrect pair of genes. Out of them, the novice user could find the second pair of genes, when asked to try again by using glasses. This indicates the usefulness of depth perception because of the glasses, though its not significant result due to only one case. All remaining participants could find both the pairs of genes correctly.

6.7.10 Effect of multiple views in ADN-Viewer

Looking at 3D DNA structure from different angles by rotating a sequence is different from having multiple views of a 3D DNA structure. Having "Multiple views" is to have different perspectives of looking at one 3D DNA structure. In ADN-Viewer, it is possible in two different ways.

1. Enable classical view to see top, front, side and perspective views of one DNA structure
2. See 3D DNA structure with the emphasis on the type of genomic information it contains, i.e. from gene to chromosome levels.

The second type of multiple viewing is out of scope for this study as the tasks require using only the trajectory presentation of a DNA structure. To assess the first type of multiple viewing, we asked the participants to rate this feature and mention this feature's importance in exploring the 3D DNA structure. We received following response.

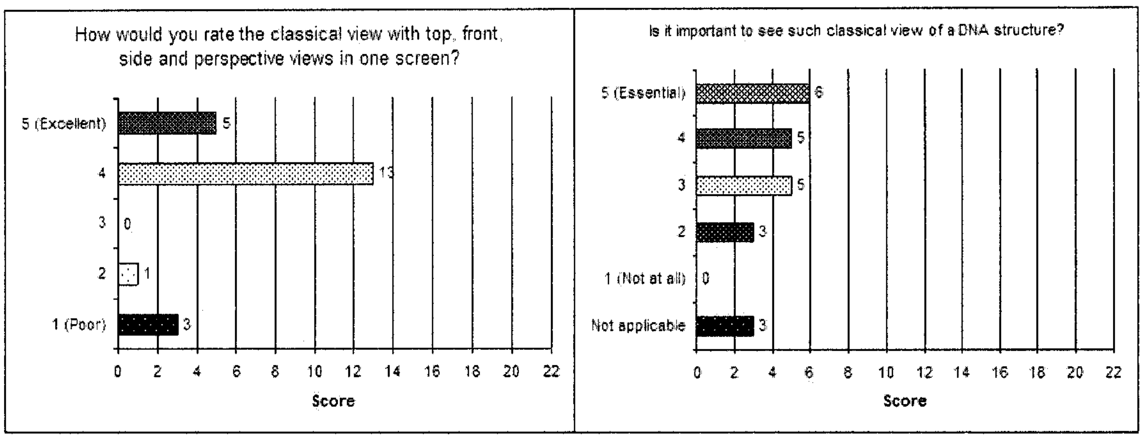


Fig. 6. 14 Reponses about Multiple Views in ADN-Viewer

The majority rating is 4 for this feature, though very few actually used this feature for completion of tasks. One participant mentioned that "(use of this feature) depends on the context, this is not the view I use in general". When asked its importance, there is no conclusive result. One of the participants responded that it is an essential feature "to study how it can interact with other things like toxicants and DNA molecules". The response was mixed because of its use being based on context. It becomes important point to observe in future study, how participants react to its usefulness in different contexts.

6.7.11 Effect of colors in ADN-Viewer

In ADN-Viewer, developers have taken extra care when choosing colors for 3D DNA structure. By default, DNA sequences are shown in yellow; when participant enables the genes, genes are shown in yellow and inter-gene zones are shown in violet color. We asked the participants to rate the color scheme used in ADN-Viewer.

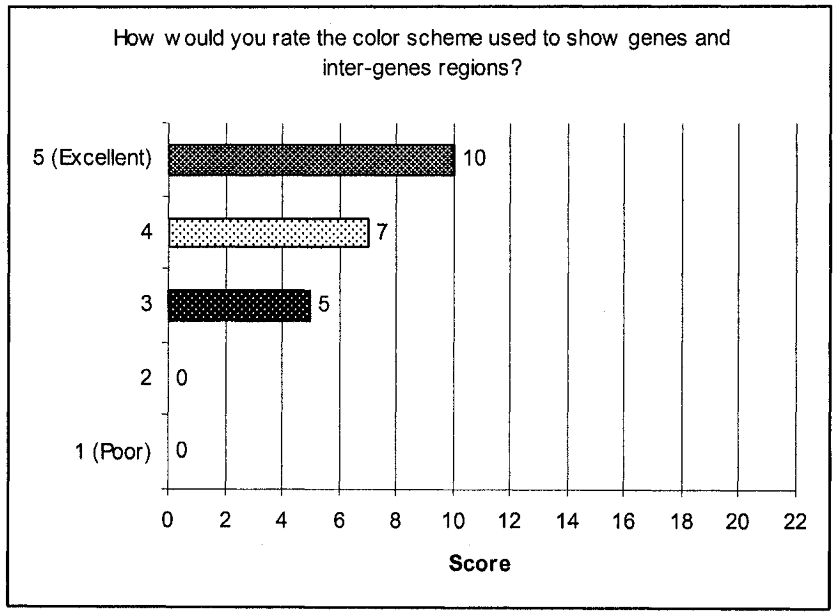


Fig. 6. 15 Responses about Colors in ADN-Viewer

Gene names are also displayed in yellow, when enabled. This adds in understanding the fact that genes are yellow and gene names are also yellow. Participants rated the color scheme positively as all the ratings range between 3 and 5. This matches with the theory of colors in semiotics of visual language (Saint-Martin 1987).

6.7.12 Mappings in ADN-Viewer

User actions in ADN-Viewer are limited to keyboard and mouse actions. Instead of keyboard actions to choose different modes, we focus on the mappings which, participants think are natural for navigating and exploring 3D DNA structure. In ADN-Viewer study, the results from the navigability based questions appear to match the mapping related questions. We asked the participants to mention their natural mouse actions for going towards and away from the 3D DNA structure, and going around the 3D

DNA structure. We received responses with the majority participants agreeing with the current set of mouse actions.

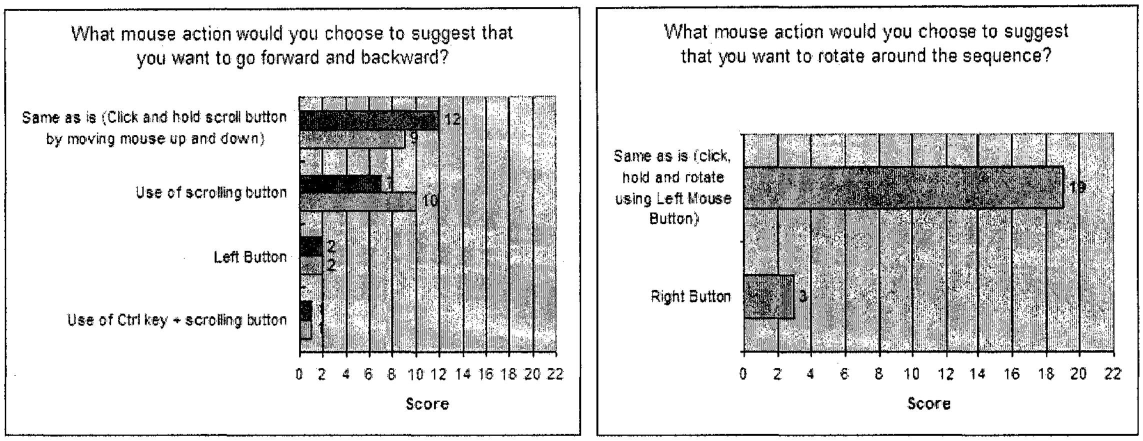


Fig. 6. 16 Mappings Suggested by Participants for ADN-Viewer Navigation

Mouse action for forward and backward has a contender action, "use of scroll button" in the mouse. Many participants felt that zooming in and out can be much easier by just scrolling the wheel without having to press it. For rotating the sequence, except some individual suggestions, majority of the participants feel that the current mouse action is fine. One participant mentions though that "it (rotation) should be able to initiate anywhere".

6.7.13 Responsiveness of ADN-Viewer

About the responsiveness, we asked 2 straightforward questions to the users.

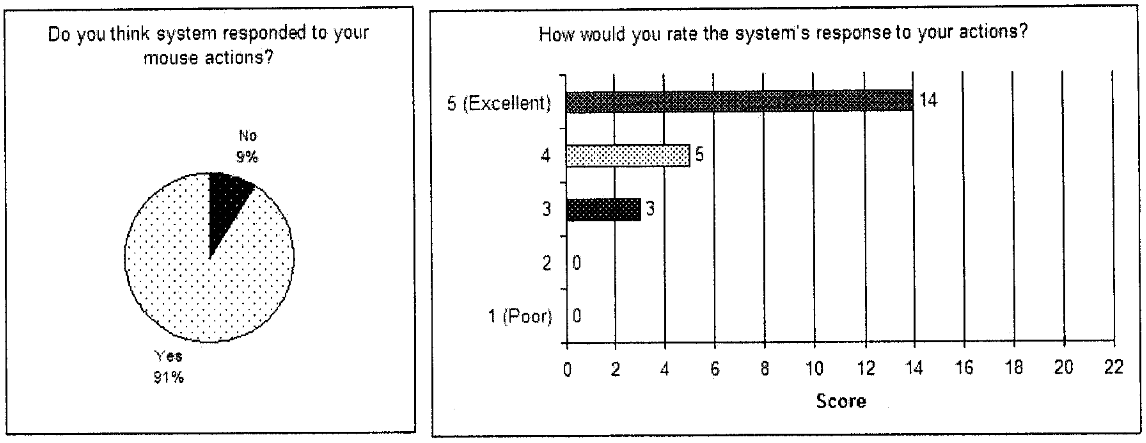


Fig. 6. 17 Responsiveness of ADN-Viewer

91% participants asserted positively about system's responsiveness. Also the ratings for the responsiveness are impressive as the highest score 14 is for rating 5.

6.7.14 Effect of Contextualization on participants

When asked whether the neighborhood of a DNA sequence can be viewed, we received a 82% positive response. The importance of looking at one gene was also confirmed by majority score of 5 which is essential.

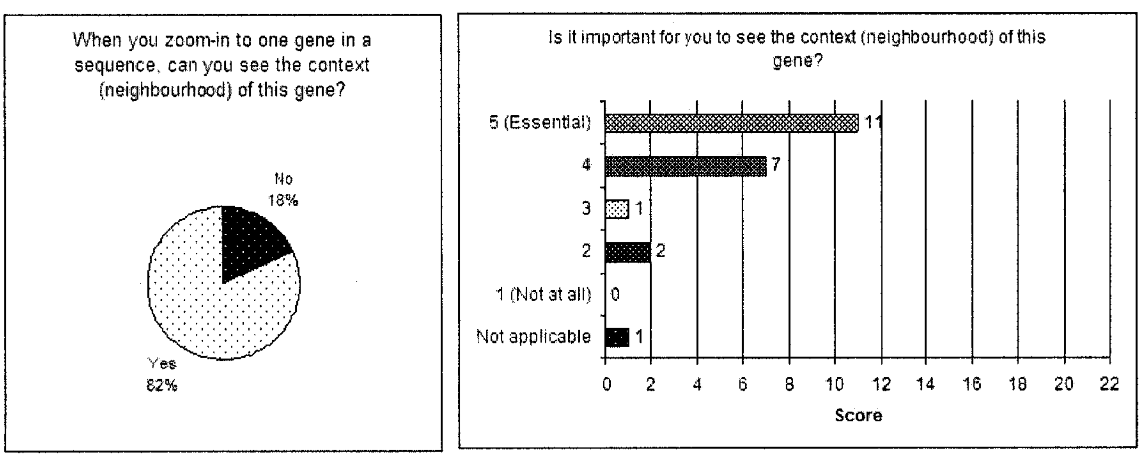


Fig. 6. 18 Importance of Contextualization in ADN-Viewer

From these responses, it is clear that it is important to see the context when zooming into one gene. Even though, majority of the participants agreed that they could see the context, still we summarized the responses for one more question which is asked to know how comfortable it is to see the neighborhood.

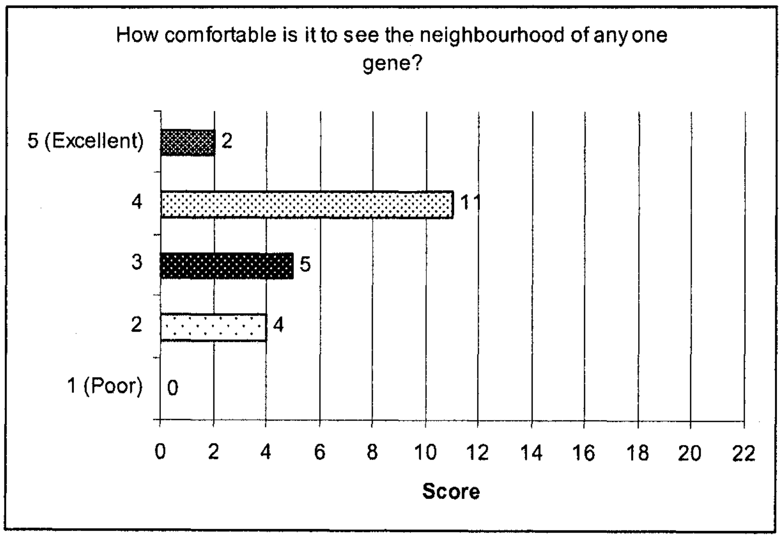


Fig. 6. 19 Comfort Level in Exploring the Context in ADN-Viewer

One observation here is the trend to rate it as 2, 3 and 4 than 5. This means that participants didn't think that it was perfectly comfortable to see the neighborhood. One reason for such rating appears from a comment by an intermediate user as "(I) should be able to scroll and see the neighbouring genes". The zoomed in gene remains fixed at the central location, only interaction available now is through rotation. Future developments can consider more freedom for user interaction when zoomed-in to one gene.

6.8 Concluding Remarks

In this chapter, we presented the "Comprehensibility Study of ADN-Viewer". This study was aimed at validating the set of comprehension criteria of Chapter 4.

This study was done on a scientific visualization environment as compared to immersive art environment of OSMOSE. According to its developers, ADN-Viewer is helpful in analyzing the DNA sequences for their 3D structures. For the study, we selected two tasks that ADN-Viewer's developers thought are typical in nature and effective to perform with the help of ADN-Viewer. We found that first task is completed by 86% of the participants where they could compare the sequences. Also, in the second task, two pairs of genes were found out by 59% of the participants and 41% participants could identify at least one pair of genes. We know that this result will gain more strength if the number of participants is increased.

In this formal usability study, we conducted a series of 11 test sessions by following a usability testing process described in Appendix B. We collected user's reactions and presented summary results. In this study, we found that thoughtful use of right colors, good navigability, and interesting animation technique for zooming onto one gene and satisfactory responsiveness as highlights of ADN-Viewer. We also discover that the context of use or participants' different purposes behind analyzing the DNA structures makes a significant impact on their responses.

Participants in this study also suggested some invaluable improvements or the problem areas in ADN-Viewer. Even if the feature of zooming onto one gene, when clicked was appreciated by the participants, from their responses, we also exposed the fact that the random path, that this feature takes to zoom onto one gene, disturbs participant's orientation and he/she feels lost. Also, "legibility" and "directionality" criteria are the other areas which need improvements. Gene names were disliked by some of the participants as they could not read them sometimes. As ADN-Viewer is developed for a specific user group, participants expressed their wish to see the right terminology to indicate direction of DNA sequence. For example, 3' and 5' instead of "start" and "end". This observation also reaffirms the addition of "directionality", as a new criterion found after the first case study, "Comprehensibility Study of OSMOSE".

One of the constraints of this study was the lack of the original setup for ADN-Viewer. The immersive environment, VENISE, which the developers of ADN-Viewer have prepared for the user interaction with DNA structure, was not available at Concordia University. We had to limit our observations about effect of presence to the effectiveness of simpler version of glasses. Hence, the responses for the use of these glasses reconfirm this fact that these glasses are not an effective way of having stereoscopic view of 3D DNA structure.

Finally, it was again one more excellent opportunity where we acquired a chance to conduct such a series of usability test sessions on a scientific visualization environment, ADN-Viewer. Without the co-operation of Dr. Gherbi, it was not possible to choose the typical tasks and the right user group for such visualization environment. A future Study of ADN-Viewer is planned to be conducted in Paris using the immersive environment, VENISE. We are confident that this future study will shed more light on the visual communication process between visualization environment and its user.

Chapter 7: CONCLUSIONS AND FUTURE WORK

This chapter provides brief summary of our research contributions, conclusions and directions for the future work.

7.1 Summary of Contributions

It is well established that computer-based interactive visualization environments, assist humans in discovering something new about data that they did not expect or in confirming something they did expect. They facilitate the human cognitive process of visualization. But, it is important to assess these visualization environments for their effectiveness in comprehension of information – the main intent of using any visualization environment.

There are usually specific intentions behind developing different visualization environments with different "visual representations" and "interaction styles and techniques". But, when users use these visualization environments, they have their own set of intentions for using them. Visualization Environments can be called as effective if these two sets of intentions match and the gap in comprehending information is small. In our research, we have tried to explore whether it is possible to characterize this comprehension gap between visualization environment and its users.

We have adapted Donald Norman's theory of Gulf of execution and evaluation to describe this comprehension gap. We have used "Model Human Processor" and "Model for Visualization Environment" for the two sides of this gap thus making this abstract concept more concrete. By looking at the nature of communication between them, we have further proposed that Aaron Marcus' visual communication principles can be used to characterize this gap. We also incorporated Norman's cognitive principles into this Marcus' Visual Communication principles by considering the cognitive nature of user's "visualization" process. Together this has yielded a collective set of assessment criteria for comprehensibility in visualization environments.

To validate proposed set of criteria, we have chosen two case studies – an immersive art environment and a scientific 3D visualization environment and conducted two usability studies. Criteria are observable goals (Padda 2003) and hence, we collected lot of observations to understand user's reactions and the reasons behind them. We designed the questionnaires which were related to criteria to be validated. Questionnaire responses form another important evidence for relevance and importance of many of the proposed set of criteria. The observed results were then analysed and compared to the expectations.

7.2 Conclusions

The cognitive process of visualization helps humans in the comprehension process. "Computer-based visualization environments" facilitate visualization of concepts or data that are not readily available in the visual form. We propose to assess this facilitation by observing the user's physical actions to the visualization environments responses and by assessing the "visual representation" itself.

7.2.1 Norman's Gulf of execution and evaluations:

In "Comprehensibility Study of OSMOSE", gulf of execution is less as no training period is required to use OSMOSE and user's physical actions are quite intuitive. This is a good example of direct manipulation interface and the concept of using the physical action for navigation is appreciated by majority of the participants. Regarding gulf of evaluation, feedback is sometimes slow in OSMOSE. Also, sense of direction is missing sometimes as this abstract world does not have familiar structure; hence, user sometimes feels to have lost control.

In Comprehensibility Study of ADN-Viewer, gulf of execution is the one that gets created using mouse and keyboard. But, as users are familiar with similar software, they are used to using these mouse actions. Hence, conventions play a positive transfer effect on participants of this study. Gulf of evaluation is evident in the "visual representation" itself where, initially, DNA sequence trajectory is not familiar to many participants. Effect of depth perception is different with different variables. Low-cost glasses do not have significant impact; though having large projection improves the user experience and proves to have positive effect on comprehension.

7.2.2 Validation of Criteria

With the help of two usability studies, we have tried to validate the comprehensibility criteria by assessing visualization environment's effectiveness in assisting users to understand "visual representation" shown to them and in achieving their goals successfully. The criteria, for which observations and participants responses could be analyzed, can be summarized as given in table 7.1.

Table 7. 1 Validation Covered for Comprehensibility criteria in Two Case Studies

Assessment Criteria for Comprehensibility in 3D Visualization Environments	Comprehensibility Study of OSMOSE	Comprehensibility Study of ADN-Viewer
Consistency		✓
-Internal		
-External		
-Real world	✓	
Navigability	✓	✓
Clustering	✓	✓
Affordance	✓	✓
Constraints	✓	✓
Dynamism	✓	✓
Depth Perception		✓
Directionality	✓	✓
Simplicity		✓
Clarity/Intuitiveness		✓
Distinctiveness	✓	✓
Emphasis	✓	✓
Legibility	✓	✓
Readability	✓	✓
Symbolism	✓	✓
Multiple views		✓
Effect of color	✓	✓
Mapping	✓	✓
Responsiveness	✓	✓
Contextualization		✓

Thus, this table shows that most of the criteria are relevant and important to 3D visualization environments' assessment. We present this work as a starting point for the research on measurement of the effectiveness of visualization environments. .

7.3 Future Work

A set of criteria that we have offered is a set of observable goals. It provides a first step if we want to work towards devising a set of metrics for each of these criteria. The metrics mentioned in Chapter 2, can provide as a starting point for this research.

Further, we notice that this set of criteria is related to two other important factors: first, type and category of visualization environment and second, user persona. Depending on the type of visualization, we observed that a specific subset of these criteria is more important than others. Also, domain knowledge and visualization environment's knowledge of users have effect over user's comprehension process. These two important factors should be studied further in detail. Some of the criteria like intuitiveness, symbolism and depth perception need more validation to understand their significance in user's comprehension process. User interaction is the real power of visualization environment and hence, the readings about this set of criteria with visualization environment using different interaction styles and techniques needed to be carried out. In our scope, we could assess the navigation and analysis tasks, but object or data manipulation is one more task that needs different set of user interaction styles and which has different effects on user's comprehension process. Hence, as future work validation of these criteria for this task also needs to be undertaken.

Empirically assessing visualisations with users is often difficult to organise and is costly in terms of time, money, and human resources. Formalism in usability testing process itself is a significant goal that is yet to be achieved in the human computer interaction domain. From our experience of conducting usability studies, we can say that a larger number of usability studies need to be performed to validate the usability testing process we have used.

Visualisation is still an evolving area and there is definitely scope for development of novel visualization environments that are effective for the purpose that they are used for. Along with this development work, it is also necessary to build an evaluation framework for assessment of visualization environment. This thesis provides one approach to start the building of such a framework based on the sound foundations of cognitive psychology and visual communication. We hope that the visualization environment development process gains some interesting insight from this research.

References

Ahlberg, C & Shneiderman, B 1994, 'Visual information seeking: tight coupling of dynamic query filters with starfield displays', in *Conference on Human Factors in Computing Systems*, ACM Press New York, NY, USA, Boston, Massachusetts, United States, pp. 313 - 317.

Atkinson, RC & Shiffrin, RM 1968, 'Human Memory: a proposed system and its control processes', in KW Spence & JT Spence (eds.), *The Psychology of Learning and Motivation: Advances and Theory*, vol. 2, New York: Acemdemic Press.

Barber, P 1988, *Applied Cognitive Psychology*, London: Methuen.

Barry, AM 1997, *Visual Intelligence: Perception, Image, and Manipulation in Visual Communication*, SUNY Press.

Bowman, DA, Johnson, D. B., and Hodges, L. F. 1999a, 'Testbed evaluation of virtual environment interaction techniques', in *The ACM symposium on Virtual reality software and technology*, ACM Press New York, NY, USA, London, United Kingdom, pp. 26 - 33.

Bowman, DaH, L 1999b, 'Formalizing the Design, Evaluation, and Application of Interaction Techniques for Immersive Virtual Environments', *The Journal of Visual Languages and Computing*, pp. 37-53.

Brath, R 1997, 'Metrics for effective information visualization', in *IEEE Symposium on Information Visualization*, pp. 108-111, 126.

Bruner, J 1966, *Toward a Theory of Instruction*, Cambridge, MA: Harvard University Press. http://tip.psychology.org/bruner.html.

Card, SK, Moran, TP & Newell, A 1983, *The Psychology of Human-Computer Interaction*, Lawrence Erlbaum Associates, Inc., New Jersey, USA.

Cron, MT 2005, *Explanation of "Depth Perception"*. from www.ferris.edu/htmls/academics/course.offerings/cronm/GLOSSARY.html.

Davies, C 2001, *"Changing Space: Virtual Reality as an Arena for Embodied Being"*, New York: Norton.

Gabbard, JLH, D. Swan, J.E., II 1999, 'User-centered design and evaluation of virtual environments', in *Computer Graphics and Applications, IEEE*, vol. 19, pp. 51 - 59, Nov.-Dec.

Gaver, W 1991, 'Technology Affordances', in *Human Factors in Computing Systems CHI'91*, eds. SP Robertson, GM Olson & JS Olson, Addison-Wesley, Reading, MA, pp. 79-84.

Gibson, JJ 1979, *The Ecological Approach to Visual Perception*, Boston: Houghton Mifflin.

Hansen, CD & Johnson, CR (eds.) 2005, *The visualization handbook*, Amsterdam ; Boston : Elsevier-Butterworth Heinemann.

Hérisson, J, Férey, N, Gros, P-E, R., G & O., M 2005, '3D Visualization and Exploration of Huge Genomic Structures', in *4th World Congress of Cellular and Molecular Biology*, Potiers, FRANCE.

Hewett, Baecker, Card, Carey, Gasen, Mantei, Perlman, Strong & Verplank 2004, *Definition of HCI*, ACM SIGCHI. from http://sigchi.org/cdg/cdg2.html.

Hinckley, K, Pausch, R, Goble, JC & Kassell, NF 1994, 'Passive real-world interface props for neurosurgical visualization', in *the SIGCHI Conference on Human Factors in Computing Systems: Celebrating interdependence*, ed. SD B. Adelson, and J. Olson, Eds., ACM Press, New York, NY, Boston, Massachusetts, United States, pp. 452-458.

Hu, HH, Gooch, A. A., Thompson, W. B., Smits, B. E., Rieser, J. J., and Shirley, P. 2000, 'Visual cues for imminent object contact in realistic virtual environment', in *Conference on Visualization '00*, IEEE Computer Society Press, Los Alamitos, CA, Salt Lake City, Utah, United States, pp. 179-185.

Huk, A 1999, *Seeing in 3D*. from http://www-psych.stanford.edu/~lera/psych115s/notes/lecture8/.

Immersence 1995-2005. from http://www.immersence.com/index.html.

Javahery, H 2003, *Pattern-Oriented Design for Interactive Systems*, Concordia University.

Juarez-Espinosa, O 2003, 'CAEVA: cognitive architecture to evaluate visualization applications', in *Seventh International Conference on Information Visualization*, pp. 589-594.

Li, Q 2005, *WizUse: A Web-based Wizard for Supporting Usability Testing Processes and Practices*, Concordia University.

Lindsay, PH & Norman, DA 1977, *Human Information Processing: An Introduction to Psychology, Second Edition*, New York: Acedemic Press.

Lowe, D 1985, *Perceptual Organization and Visual Recognition*, Kluwer Academic Publishers.

Marcus, A (ed.) 1995, *Principles of Effective Visual Communication for Graphical User Interface Design,* Second edn, San Francisco, Calif. : Morgan Kaufmann Publishers.

Mazur, J & Jaynes, C 2002, *Deploying New Tools for Investigating Collaboration in Immersive, Non-Restrictive Environments - The Metaverse Situational Tracker*. from http://metaverselab.org/project/papers/CSCW%202002-Mazur.pdf.

Microsoft 2005, *Visualization and Interaction for Business and Entertainment*. from http://research.microsoft.com/vibe/.

Model of Visualization 1999. from http://www.siggraph.org/education/materials/HyperVis/abs_con1/model.htm.

Nakakoji, KT, A.; Yamamoto, Y. 2001, 'Cognitive effects of animated visualization in exploratory visual data analysis', in *Fifth International Conference on Information Visualisation*, pp. 77-84.

Norcia, AM 2005, *Depth Perception Definition*. from www.ski.org/AMNorcia_lab/General/terms.html.

Norman, DA 1988a, 'The Psychology of Everyday Action', in *The Psychology of Everyday Things*, New York: Basic Books.

Norman, DA 1988b, *The Psychology of Everyday Things*, New York: Basic Books.

Norman, DA 1988c, 'The Psychopathology of Everyday Things', in, New York: Basic Books.

Nunez, DaB, E. 2001, 'Cognitive presence as a unified concept of virtual reality effectiveness', in *The 1st international Conference on Computer Graphics, Virtual Reality and Visualisation*, ACM Press, New York, NY, Camps Bay, Cape Town, South Africa, pp. 115-118.

Nunez, DaB, E. 2003, 'Conceptual priming as a determinant of presence in virtual environments', in *2nd international Conference on Computer Graphics, Virtual Reality, Visualisation and interaction in Africa*, ACM Press, New York, NY, Cape Town, South Africa, pp. 101-108.

On-line Library of Information Visualization Environments 1997, University of Maryland, College Park. from http://www.otal.umd.edu/Olive/.

Oxford English Dictionary 2005, Oxford University Press.

Padda, HK 2003, *QUIM Map: A Repository for Usability/Quality in Use Measurement*, Concordia University.

, 'Panel: Metrics and Benchmarks for Visualization'1995, in *Proceedings of the 6th Conference on Visualization*, IEEE Computer Society Washington, DC, USA, p. 422.

Plaisant, C, Milash, B, Rose, A, Widoff, S & Shneiderman, B 1996, 'LifeLines: visualizing personal histories', in *Conference on Human Factors in Computing Systems*, ACM Press New York, NY, USA, Vancouver, British Columbia, Canada, pp. 221 - ff.

Preece, J, Rogers, Y, Sharp, H, Benyon, D, Holland, S & Carey, T (eds.) 1994a, *Human Computer Interaction*, Addison-Wesley Publishers.

Preece, J, Rogers, Y, Sharp, H, Benyon, D, Holland, S & Carey, T 1994b, 'Perception and Representation', in *Human Computer Interaction*, Addison-Wesley Publishers.

Robertson, P & De Ferrari, L 1994, 'Systematic Approaches to Visualization: Is a Reference Model Needed?' in RAea Rosenblum (ed.), *Scientific Visualization: Advances and Challenges*, New York : Academic Press.

Rushmeier, H, Barrett, H., Rheingans, P., Uselton, S., and Watson, A. 1997, 'Perceptual measures for effective visualizations', in *The 8th conference on Visualization '97*, eds. R. Yagel & H Hagen, IEEE Computer Society Press Los Alamitos, CA, USA, Phoenix, Arizona, United States, pp. 515 - 517.

Saint-Martin, F 1987, 'The Visual Variables', in *Semiotics of Visual Language.*

Shneiderman, B 1983, 'Direct Manipulation: a step beyond programming languages', in *IEEE Computer*, vol. 16, pp. 57-69,

Shneiderman, B 1992, *Designing the User Interface: Strategies for Effective Human-Computer Interaction,* Second edn, Addison-Wesley.

Smolnik, SN, L.; Knieps, T. 2003, 'Mental representations and visualization processes in organizational memories', in *Seventh International Conference on Information Visualization*, pp. 568- 575.

Spence, R 2001, 'Information VIsualization'.

Vince, J 2004, *Introduction to Virtual Reality*, Springler-Verlag London.

Wilkins, B 2003, *MELD: A PATTERN SUPPORTED METHODOLOGY FOR VISUALISATION DESIGN*, The University of Birmingham.

Williamson, C & Shneiderman, B 1992, 'The dynamic HomeFinder: evaluating dynamic queries in a real-estate information exploration system', in *Annual ACM Conference on Research and Development in Information Retrieval*, ACM Press New York, NY, USA, Copenhagen, Denmark, pp. 338 - 346.

Winckler, MA, Palanque, P., and Freitas, C. M. 2004, 'Tasks and scenario-based evaluation of information visualization techniques', in *The 3rd Annual Conference on Task Models and Diagrams*, ACM Press, New York, NY, Prague, Czech Republic.

Wiss, U & Carr, D 1998, *A Cognitive Classification Framework for 3-Dimensional Information Visualization*, Luleå University of Technology, Lule°a, Sweden, Research report LTU-TR--1998/4--SE, 971 87.

Zhou, H, Chen, M., and Webster, M. F. 2002, 'Comparative evaluation of visualization and experimental results using image comparison metrics', in *Conference on Visualization*, VISUALIZATION. IEEE Computer Society, Washington, DC, Boston, Massachusetts, pp. 315-322.

Appendix A - Details of "Comprehensibility Study of OSMOSE"

Usability Testing Process

We start with the usability test process we used. This process is the work of team members in Human Centered Software Engineering group at Concordia University. (Li 2005)

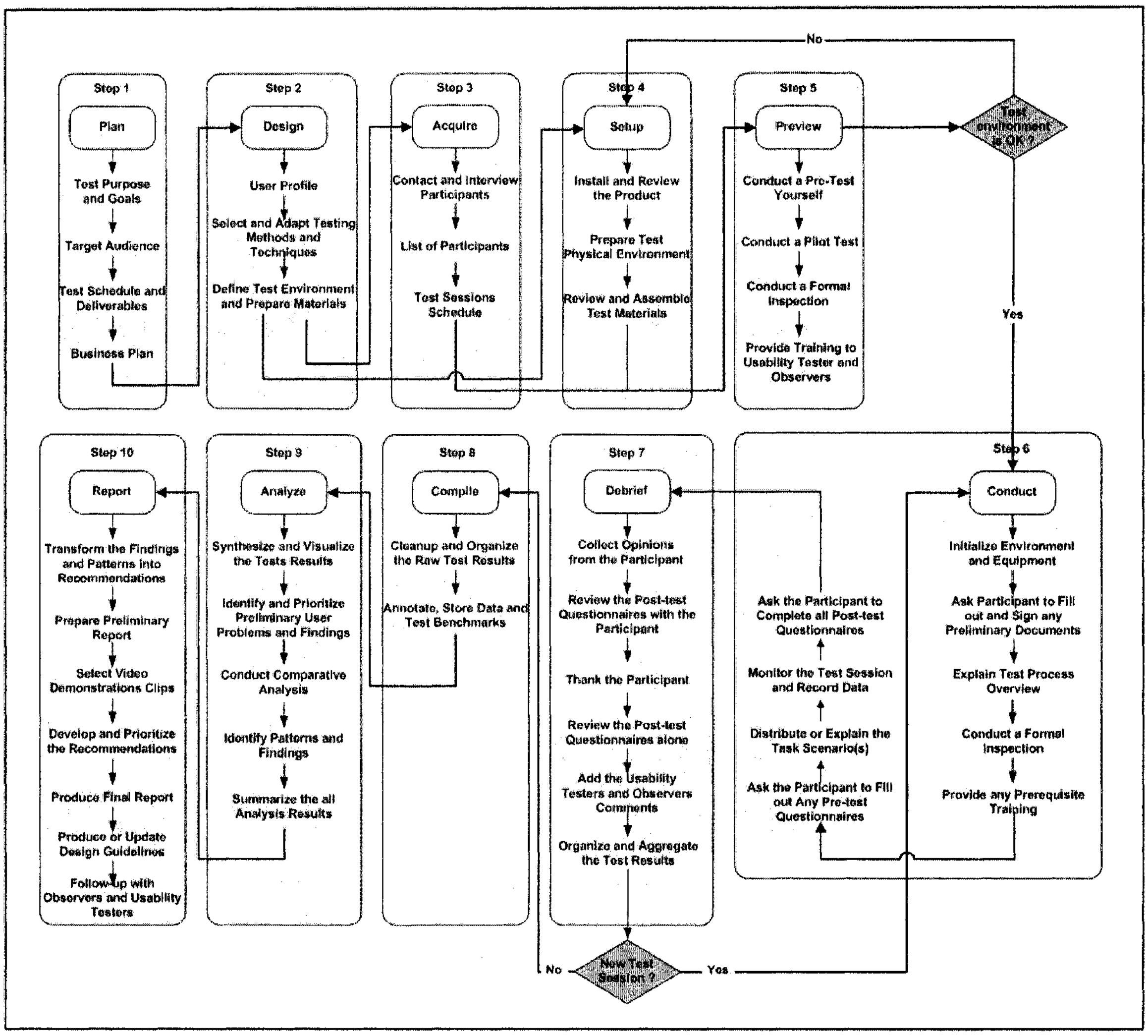


Figure 1A Usability Testing Process

Most of the major steps in this process were covered during "Comprehensibility Study of OSMOSE". Here, we provide the details which are not mentioned in Chapter 5.

"PLAN" - Roles and responsibilities

Each team member had a specific role in the test session. The responsibilities of each role are given below in the sequence in which they take part in the test session:

- **Welcomer:** welcomes the participants and gets the consent form and pre-test questionnaire filled in by the participant.
- **Monitor:** talks to the participant and monitors the test session from the beginning till the end of the test. He/she instructs the participant about the navigation actions before the test starts, helps the participant if he/she needs help during the test, and puts on or removes HMD and vest on the participant.
- **Data Loggers:** there were two types of data loggers. One who writes the observations on paper manually and another who adds event tags in "Morae Remote Viewer" software.
- **Interviewer:** interviews the participant by asking the questions from post-test questionnaire and filling out answers for them.
- **Technician:** tests all the test equipments before the test and adjusts different camcorder positions for the test and interview.

"DESIGN" – Preparing Test Documents

Samples of test documents prepared are presented in the following order:

- Consent Form
- Osmose User Evaluation
- Post-test questionnaire

No screening questionnaire was prepared as OSMOSE is designed to be used by general public.

CONSENT FORM TO PARTICIPATE IN RESEARCH

This is to state that I agree to participate in a research study being conducted at the Department of Computer Science and Software Engineering, Concordia University. The study is part of the HMD project funded by NSERC-NEW Media Initiative Program. The research is conducted by an interdisciplinary group of researchers at Concordia University and the University of Montreal. The main investigators are: Dr. Sudhir Mudur, Dr. Ahmed Seffah, Dr. Philippe Lalande, Dr. Rajamohan Ganesan and In collaboration with the artist Char Davies

A. PURPOSE OF THE STUDY

I have been informed that the purpose of the research is to design and develop a prototype of a new HMD (Stereoscopic Head Mounted Display) system that optimally meets the requirements for use in art environments such as those created by the artist Char Davies, one of Canada's most renowned new media artists. The current HMD system have been exhibited widely, including the San Francisco Museum of Modern Art, the Australian Center for the Moving Image (Melbourne), the Barbican Centre (London), the Museum of Monterrey (Mexico), as well as the National Gallery of Canada and the Montreal Musée d'Arts Contemporains.

B. PROCEDURES

Dr. Seffah and his team (Seffah@cs.concordia.ca Phone 514 848 2424 ext. 3024) are charge of the study. The study designed to ask artists and users about their experiences using the current HMD (Stereoscopic Head Mounted Display) system. You are being asked to answer to a questionnaire and to accomplish a certain number of tasks using the HMD. This should take no more than 1 hour of your time.

We anticipate no risk to you as a result of your participation in this study other than the inconvenience of the time to complete the questionnaire and to use the current HMD system. While there may be no immediate benefit to you as a result of your participation in this study, it is hoped that we may gain valuable information about your experiences using HMD so that we can help to improve their usefulness and usability.

The information that you give us and that we will collect automatically will be stored in an anonymous way in a database with no information that could identify you. Results from the survey will be reported only in aggregate form in scientific communications like articles, workshops, or conference presentations. A summary of the results will be posted the project Web site (http://hci.cs.concordia.ca/www/hmd). If you wish to receive the results of this study, please check the box below and provide an e-mail address.

Name:
☐ **Mail address**:
....

C. CONDITIONS OF PARTICIPATION

- I understand that I am free to withdraw my consent and discontinue my participation at anytime without negative consequences.
- I understand that my participation in this study is CONFIDENTIAL (i.e., the researcher will know, but will not disclose my identity)
- I understand that the data from this study may be published.

I HAVE CAREFULLY STUDIED THE ABOVE AND UNDERSTAND THIS AGREEMENT. I FREELY CONSENT AND VOLUNTARILY AGREE TO PARTICIPATE IN THIS STUDY.

NAME (please print) ____

SIGNATURE ____

If at any time you have questions about your rights as a research participant, please contact Adela Reid, Research Ethics and Compliance Officer, Concordia University, at (514) 848-7481 or by email at areid@alcor.concordia.ca.

Osmose User Evaluation

Thank you for completing this evaluation form based on your experiences with the "Osmose" environment. All responses will remain anonymous and results will be used solely for research purposes.

Name: ____

Age: _____ **Gender:** ☐ Male ☐ Female

What is your first language? ☐ English ☐ French ☐ Other Please specify: ________

What is your field of study (expertise/ domain area)?

____

What is your highest level of education?

____

What is your current position/employment?

____

Would you consider yourself any of the following? Please check all that apply:

☐ Artist
☐ Designer
☐ Computer graphics specialist
☐ Other

If relevant, how many years have you been an artist, designer, or working with computer graphics?

☐ <1 year ☐ 1-3 years ☐ >3 years ☐ Not applicable

How long have you been using computers?

☐ <6 months. ☐ <1 year ☐ 1-3 years ☐ >3 years

Do you wear glasses or contact lenses due to a nearsightedness problem with your vision?

☐ Yes ☐ No

Do you like to visit museums or art exhibitions?

☐ Yes ☐ No

Do you like to know about innovations in fine arts and/or engineering?

☐ Yes ☐ No

Have you ever tried a virtual reality environment?

☐ Yes ☐ No

Please list some of your hobbies and interests below:

Thank you! ☺

Post-Test Questionnaire

1. What are three main activities you performed with "Osmose"? **

1. ______________________________
2. ______________________________
3. ______________________________

** This can include navigation, exploratory tasks, looking for a specific landmark or "world", wanting to go in a specific direction, etc.

2. Which of the following did you see in the virtual world?

☐ Tree
☐ Leaf
☐ Cloud
☐ Forest
☐ Pond
☐ Subterranean Earth
☐ Abyss: a very deep region
☐ Clearing
☐ Text
☐ Source Code
☐ Other: (please specify) ______________________________

3. What were the colours you saw?

____

4. Did you want to touch what you are looking at?

☐ Yes ☐ No

5. Did you try to touch what you are looking at?

☐ Yes
What happened when you tried?

____

☐ No
Why did you decide not to touch anything?

____

6. What action would you choose to suggest that you want to go up and down?

Go Up: ______________________________

Go Down: ______________________________

7. **What action would you choose to suggest that you want to go forward and backward?**

Go Forward: ______________________________

Go Backward: ______________________________

8. **Did you want to go towards any particular object in the environment?**

☐ Yes ☐ No

If yes, was it because of its:

☐ Size
☐ Placement
☐ Texture
☐ Color
☐ Brightness
☐ Other, please specify: ______________________________

9. **Did you feel that you are really in the virtual world?**
☐ Yes ☐ No

Explain, Why: ______________________________

10. **What made you aware of the real world? (Check all that apply)**

☐ Hardware (HMD/ vest)
☐ Breathing
☐ Hands/Legs/Head movements

11. **What did you like about this environment? (Check all that apply)**

☐ New Technology
☐ Colors
☐ Sound
☐ The Theme
☐ Other ____________________

Thank you! ☺

"ACQUIRE" - Contacting Participants and Preparing Test Schedule

As the artwork is exhibited in museums, no special group of participants was required to conduct this test. We invited 15 participants to experience OSMOSE. Some of them were doing administrative jobs, some were professors, and some were undergraduate and graduate students.

The steps taken for preparing the test schedule are as follows:

1. First contacted them by sending one common invitation email.
2. When they respond positively to participate, asked for their available dates in the month of June, 2005.
3. Collect all the available dates for interested participants, and then schedule all the participants for different time slots.
4. E-mailed every participant about the test date, time, location and directions to reach the location. Also request the confirmation from them.
5. After the receipt of their confirmation, post the test schedule for other team members who help in conducting the test.
6. Keep updating the team members for any changes in the schedule.

"SETUP" - Physical Test Environment

Two of the team members, Qing Li and Jonathan Benn set up the physical test environment for the study. We used the setup that was done for HMD study.

This setup involves reception, testing, and observation and interview areas. Each area was devoted for a specific activity during the test session.

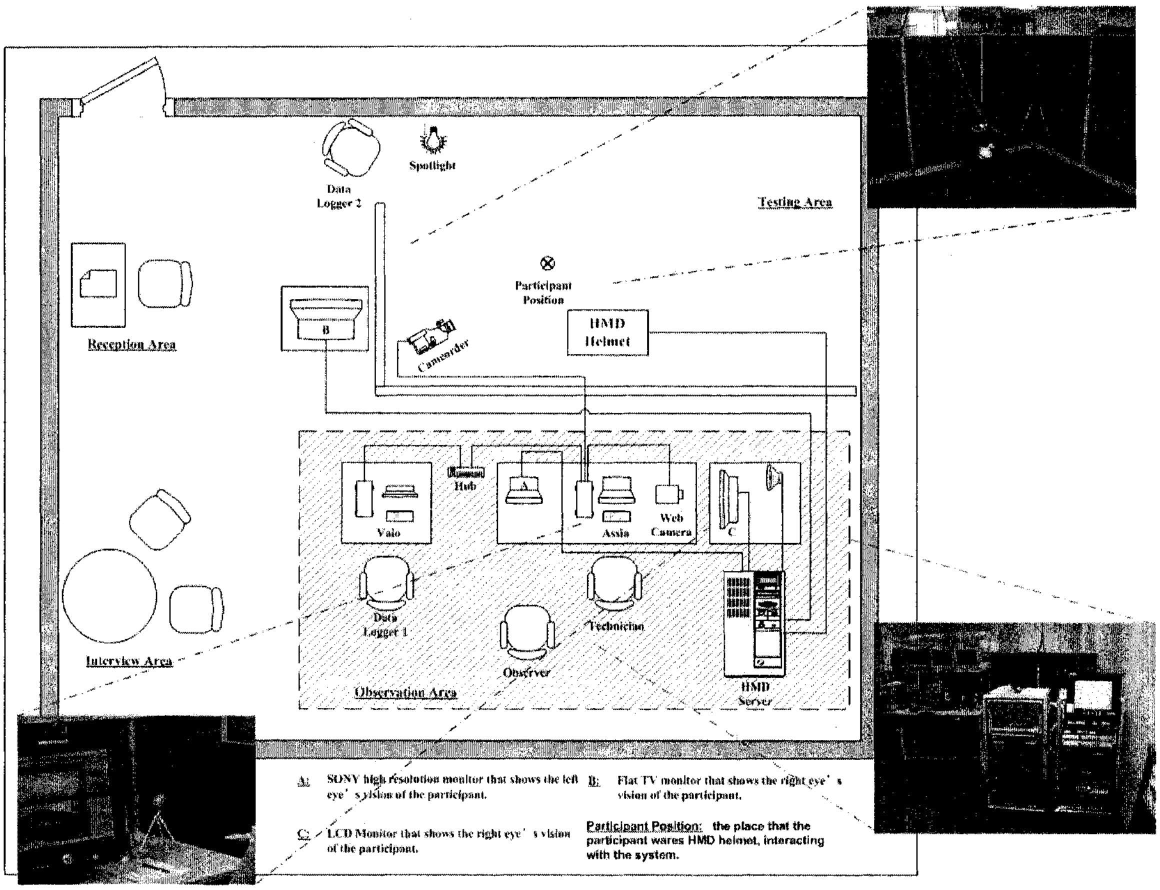


Figure 2A Physical Test Environment for "Comprehensbility Study of OSMOSE"

"CONDUCT" and "DEBRIEF" - Conducting the Test Session

Here, we enlist the steps taken during a test session.

- First the "Welcomer" greets the participant at the reception area. He/she gives a brief idea about OSMOSE to the participants and asks the participant to read and sign the consent form. Then, he/she asks the participant to fill out the "OSMOSE Participant Evaluation" form.

- "Welcomer" introduces the participant to "Monitor" who communicates with the participant throughout the test. "Monitor" explains the participants about the steps to follow and instructs the participants about the navigation actions.
- "Monitor" helps participant to wear HMD and vest. He/she instructs the participant to try out all navigation actions when the 3D Cartesian grid appears on HMD screen.
- Once the OSMOSE appears on HMD screen, "Morae data logger" enters the start of the task tag, "monitor" takes backseat as he/she should not give instructions during the 15 minutes test session. "Manual Data logger" sits near the test site and records all the observations on paper. "Morae data logger" enters "end of task" at the end of the 15 minutes test session.
- After the test session, "Monitor" helps the participant to take off HMD and the vest. "Monitor" introduces the participant to the interviewer. At this time, technician adjusts the camera angle to record the interview session.
- "Interviewer" asks every question from post-test questionnaire to the participant and fills out the participants' responses in the questionnaire. This way, participant is not burdened by answering too many questions throughout the test session.
- After the interview session, interviewer presents a small gift as token of team's appreciation towards participant for participating in the study.

Navigation Instructions

"Monitor" gives following instructions to each participant about using OSMOSE navigation actions. These instructions are listed here for reader's reference:

- Breath in to go up in OSMOSE
- Breath out to go down in OSMOSE
- Look around by turning head in all directions
- Lean forward to move forward in virtual space
- Lean backward to move backward in virtual space

"COMPILE" – Summary of User Responses

<table>
<tr><th>Post Test Questionnaire</th><th colspan="2">Participant Responses</th></tr>
<tr><td rowspan="12">1. Which of the following did you see in the virtual world?

□ Tree
□ Leaf
□ Cloud
□ Forest
□ Pond
□ Subterranean Earth
□ Abyss: a very deep region
□ Clearing
□ Text
□ Source Code
□ Other: (please specify)

(Readability)</td><td>Tree</td><td>(23)</td></tr>
<tr><td>Leaf</td><td>(20)</td></tr>
<tr><td>Cloud</td><td>(15)</td></tr>
<tr><td>Forest</td><td>(13)</td></tr>
<tr><td>Pond</td><td>(3)</td></tr>
<tr><td>Subterranean Earth</td><td>(20)</td></tr>
<tr><td>Abyss: a very deep region</td><td>(16)</td></tr>
<tr><td>Clearing</td><td>(12)</td></tr>
<tr><td>Text</td><td>(20)</td></tr>
<tr><td>Source Code</td><td>(16)</td></tr>
<tr><td>Other:(please specify)

Out of (17) , 16 mentioned white lights</td><td>• I could at times see what seemed liked pixels.
• Lines
• Some glowing lights
• Light sources (bulbs)
• Bubbles
• pink balls
• Grid and globe
• Stars and grid
• colored points, space
• formulae in the text
• Fireflies (white)
• bugs
• white cells
• things like birds
• dots (stars), fish
• points / planets
• bugs</td></tr>
<tr><td colspan="2"></td></tr>
<tr><td>2. What were the colours you saw?

(Effect of Colors)</td><td colspan="2">• It seemed like a white/green monochrome display
• Mainly sepia, some brownish green, some blue. The clarity of detail could be improved
• Black, Green, white, blue, orange
• browns, greens, yellows
• Green / Yellow / Orange / Purple
• Grey, green, white</td></tr>
</table>

	• blacks, green • Brown, Green, white • white • Neutral monochromatic and silvery colors: grays, browns, tans, etc. Some brighter more contrasting colors randomly. • Green, Golden yellow, white • Green, orange, red, sand color • Pink, white(philosophy), orange (lava), green (text), beige, muddy green (leaves) • Red, orange, white, black(text), blue • Golden (tree), red (underground), white(stars), green (text), black (background) • white (points), green(code and leaves), brown(tree), red (some points), black (remaining space) • red (lava), black (clearing), green (diff shades), blue(sky/water) • Green, black, white , copper gold • white, green, brown shades, black, red • green, brown, white, black • greens (text), browns, white, yellow • green, white, brown, reddish brown, light green(leaves) • green (text), grey (station and points) • bright orange(rocks), white (clouds and bubbles), flashy green (text), deep green (leaves) • green(letters and leaves), dark red(lava), white (bugs), brownish pink (clouds)
3. Did you want to touch what you are looking at? (Affordances)	Yes | (15) No | (8)
4. Did you try to touch what you are looking at? (Affordances)	Yes | (10) No | (14)
□ Yes, What happened when you tried?	• Nothing • You couldn't turn leafs over which would have been interesting. • nothing • usually went right through anything I wanted to touch (collide with, really) • I believe that the objects moved away from me.

	• You were not able to touch (tried to touch static thing: tree) • I landed in some different section. • you went through • went through them • light was coming from outside • You couldn't reach there to touch it • you couldn't
□ No, Why did you decide not to touch anything?	• Because it was more like looking at a scene on TV rather than an interactive video game. Moreover, the only input was through the movement, and knowing this, trying to touch would have been pointless. • didn't • Because I knew it was virtual • Didn't think • was aware that I can't • all was abstract except tree • didn't want to • light from outside • obviously not real • Knew it was an illusion
5. What action would you choose to suggest that you want to go up and down? Up: Down: (Mapping)	• I would suggest a controller worn on the hand (similar to that on the helmet) that would allow the user to "point" in the direction he wishes to move, in any direction. • tilting head up and tilting head down • raise the arms and sit down • Breathe in and out • point direction with hand (or foot if hand used for interaction) • Move my hands or arms up (soaring) and Move my hands or arms down (trying to land) • Raise your arms up and Bend down • Joystick control • expand chest and deflate chest • something natural and/or easy • Raising one hand and putting it down • Joystick control • Looking / stare up and lean forward • Hands moving up and down • Jump and sit • Raise your head and bend your legs

	• stare in upward/downward direction. • stand on toes and bend the knees to go down • raising toes and pushing heels • moving arms up / moving eyes up • moving shoulders up and down • Tip toeing yourself to go up and lower yourself to go down • thumbs up and down • open the arms to go up and sit / bend down to go down • hands up and down
6. What action would you choose to suggest that you want to go forward and backward? Go Forward: Go Backward: (Mapping)	• above • putting a foot forward, putting a foot backwards • incline the body forward and backward • lean forward and backward • as above (Note: We also need slide left & right to complete the 6 directions.) • Step forwards and backwards • take actual steps forward and backward • Joystick control • lean forward and backward • something natural and/or easy • Bend forward and backward • second joystick • lean forward and backward • Lean forward and backward • step forward and backward • Step forward and backward • step forward / backward • lean forward and backward • one foot forward and lean • lean forward and backward • lean forward and backward • step forward and step backward • hands movement (confirm) • bend forward and backward • step forward and backward

7. Did you want to go towards any particular object in the environment? □ Yes □ No If yes, was it because of its: □ Size □ Placement □ Texture □ Color □ Brightness □ Other, please specify: (Emphasis)	Yes (tree) (23) No (2) Size (5) Placement (5) Texture (8) Color (7) Brightness (10) Other, please specify: (9) • To read the text blocks • nature (ex: leaf) • Plain exploration • asked to do so • to see any other trees or leaves • raindrops on the leaves • just attraction • their number • interest as an image/object
8. Did you feel that you are really in that virtual world? □ Yes □ No Explain, Why: (Constraints)	Yes (9) No (16) Reason: • The sense of three dimensions • The resolution of what you see is so blurred. It is not very inviting. I was expecting sharp details where I could see under things. • The environment is quiet, slow but the system is responsive, the space is without border, the texture seem to be true (ex: text code) • scan lines and some gap in goggles, foot movements • Not real enough. On the other hand, the immersion is good, I felt like I was surrounded by a scene. • Because I felt that I was floating on a cloud • Apparatus so combersome • I wouldn't say fully no. The fact that I could not touch anything made me feel in the virtual world. But the hardware (vest and headmount were difficult to ignore) • The effect was not rich enough in sound, graphics(objects, images) • Carpet was visible; hear noise from outside, one of the headphones was not working properly.

	• screen resolution was poor. Flexibility to turn around was poor. Sound was more immersive • Objects are not solid, and they are sparse • light was coming from outside, the world is limited • You can see the ground • could see the light below • Light from below	
9. What made you be aware of the real world? (Check all that apply) □ Hardware (HMD/ vest) □ Breathing □ Hands/Legs/Head movements (Constraints)	Hardware (HMD/ vest)	(18)
	Breathing	(14)
	Hands/Legs/Head movements	(8)
10. What did you like about this environment? (Check all that apply) □ New Technology □ Colors □ Sound □ The Theme	New Technology	(20)
	Colors	(5)
	Sound	(13)
	The Theme	(10)
	Other, please specify: (8)	• Again, the sense of dimensions • quiet • the physicality of moving around -- like yoga class • 3D world to explore • Universe should have more feeling of immersion. Planets, starts (moving fast around you) • Its Illusive , hence its exciting • the world made her feel different at different levels • Not as interesting as it could be

"Analyze" - Observations and descriptive statistics:

The main analysis and report is presented in Chapter 5. Here, we first list actual user comments referred in section 5.6 categorized according to relevant comprehensibility criteria. Then, we present some additional descriptive statistics about the collected questionnaire responses.

User Comments:

Navigability:

- At the beginning, it should be starting in the tree somewhere
- Its (the path) circular , it doesn't matter
- Against my will, I fell in the code, so, I let it go.
- You can start (the session) at tree as its Natural at tree level
- It was more the process to navigate in the world than to explore.
- Discovered that tree is the entry point for other world

Constraints:

Logical constraints:

- When I move into the tree, I cannot feel anything, so I realized I cannot touch
- I Feel inside the world because I see objects, but I don't feel inside because I cannot interact with the objects
- Decided not to touch (knew and was aware of the limitations – that if hands are not connected to anything physically , I cannot touch)
- Touching: wasn't really an option, I went through things

Cultural Constraint:

- When I saw **bugs, leaves**, I tried to know if I wear glove, can I move something, interact with them, and cause it to change.
- Interesting, never really got the complete illusion that I was somewhere else; I knew I am standing here, wearing the helmet;
- Also, the illusion is like you are in the water, but in fact, you are actually standing on the ground, so its kind of contradiction of senses; if may be I did it in swimming pool, I will have better illusion

Dynamism:

- Lights moving, texts scrolling, so I was trying whether I could change something. Texts were crossing each other, so I tried to move backward to read it, (but I wish I could move them so that I could read).
- Little things around and here is this source of light, you see things flowing, so you get naturally attracted to that thing

Emphasis:

- Tree was a landmark, hence wanted to go towards it: first object that you see, it was something solid
- Tree is the place in the scenarios which will grab your eyes definitely
- Wanted to go towards tree: because of size, dominating object in the world, texture
- Glowing dead tree thing, stood out from everything else.
- Reason was singularity and position as there was nothing around it, brightness because it was glowing

Legibility:

- Tries to read the words in clouds, says "I am in the computer"
- One participant says "(Text) wants me to read it and know about the space."
- Reading the text: breathing data, System error, print
- Looks happy when sees word "breathing"

Readability:

- It felt like water, everything is non-solid.
- Fun when got to level of the tree
- Felt like falling in the pit (in code level)
- Pink balls were interesting; it's a very lonely world, it feels nice when these pink balls come out.
- It was not real, and too sparse, to lose track of real world
- Experience of going through things is interesting
- Theme was interesting, (there is this earth, nice pretty forest, if you go further up, it goes to white, as you further down, it goes to black)
- Tree of life: it was just Beautiful, sense of something bigger than life, it's a spiritual feeling; you are taken by it
- Being in someone else's creation was an interesting part.
- Illusive, robotic feeling, walls of words (green)
- Its weird but I feel like I can't breath (while in code world)

Symbolism:

- Tree- metaphor for tree of life
- When I found ground, I sort of fell through it. And then there was some dark text and my way up, pass the cloud and there is white environment with text
- Illusive, expected to discovery, sense of quest, exciting, metaphors

Effect of Color:

- Its scary and really dark, so, I look around to see something

- All white, so I must be in clouds., its peaceful here (that's user's inference)
- Green is repetitive, but, if the theme is mother earth, green is life and hope.

Mapping:

- entire set (HMD, vest) is cumbersome; controls are too stiff to make it natural
- It was pretty frustrating trying to move, difficult to get to things, as there was a lot of variety to see
- Movement was difficult with breathing.
- concentrating on the breathing , so couldn't explore
- If I had been using more body parts to use in the world, then I would have felt more engaged to it
- If I have to go forward in one horizontal line, it is tricky to move forward by leaning forward but not looking down

Responsiveness:

- Walls of phrases , if I move forward more walls appear
- I feel like I can move faster here (in the world between earth and code)
- Moving forward is not working here, (in the code)
- once again I can feel I cannot move faster, I want to go there, quickly enough
- Things tend to disappear when u go close to them

Additional Descriptive Statistics for OSMOSE Study:

Effect of emphasis on attention:

In "Model Human Processor" (Card, Moran & Newell 1983), when the perceived and stored encoded information is attended frequently, the probability of that representation to go in the long term memory increases. (Preece et al. 1994a) Hence, we asked whether they paid attention to any particular object in the environment, 92% that is 23 of 25 participants answered positively. Out of those 23, 19 participants wanted to go towards "tree" in OSMOSE. The most popular reason behind this attraction was "brightness".

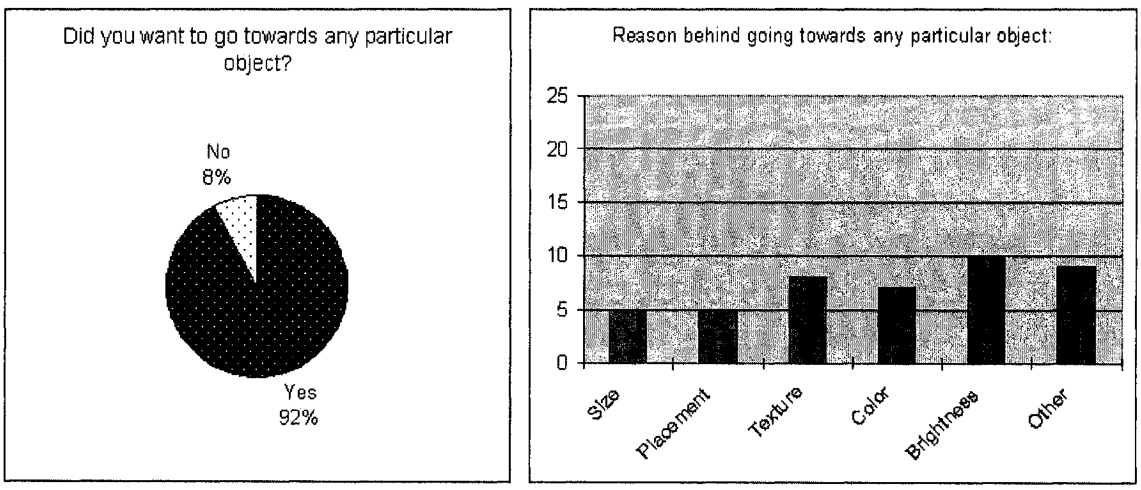
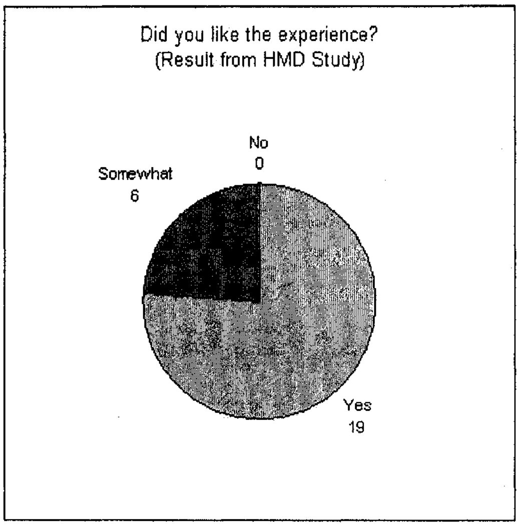


Fig. 5. 11 Attention towards a particular object

Effect of OSMOSE on enjoyment

From one HMD study results, we see that majority participants liked the experience. In "Comprehensibility Study of OSMOSE", we wanted to know what factor did they like the most about OSMOSE. Though, 10 participants said that they liked the theme, the most popular factor was "new technology". Immersive environment itself was the exciting and enjoying factor. People were excited because the technology was the one that they had never seen before as most participants tried it for the first time.



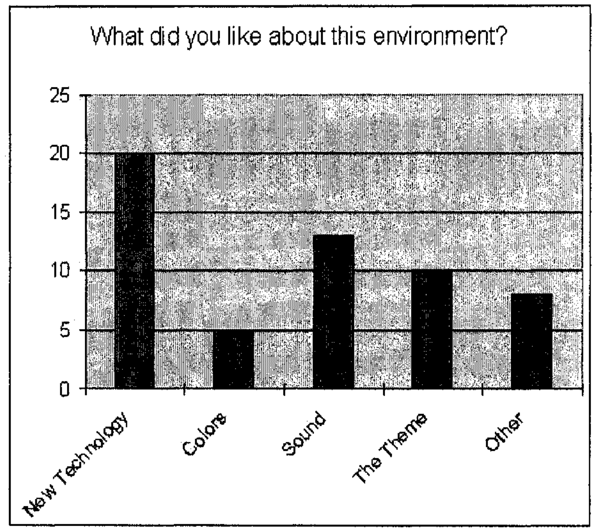


Fig. 5. 12 Reason behind liking OSMOSE

After doing this criteria-based descriptive analysis about the "Comprehensibility Study of OSMOSE", we now present a small comparative study. We compare the responses from "HMD study" users with the responses from "Comprehensibility Study of OSMOSE" users. 10 participants of HMD study responded to the post test questionnaire of "Comprehensibility Study of OSMOSE" almost 7 days after they experienced OSMOSE. We wanted to know what their responses are after this time interval.

Comparative Analysis

Here, we present an interesting result of comparing the objects seen and colors remembered in OSMOSE by two set of users. "HMD study" users responded to these questions 7 days after they experienced OSMOSE. By our understanding of "Model Human Processor", when the representations in "working memory" are attended to frequently, their probability of going in "Long term memory" increases. Here, we want to see, what the "HMD study" participants remembered after 7 days which is most probably because of the "long term memory".

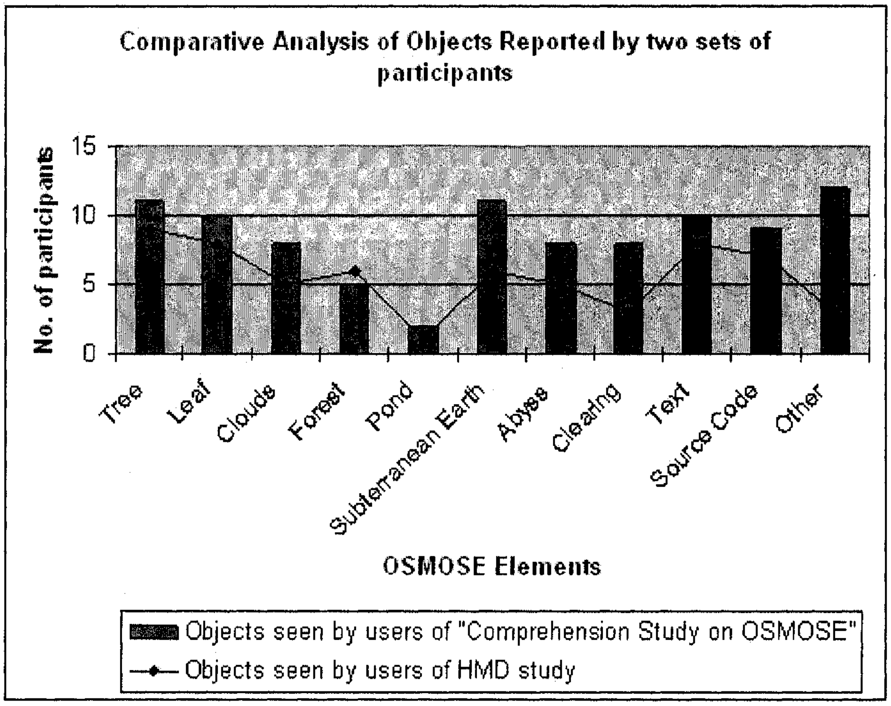


Fig. 5. 13 Results about remembering objects in OSMOSE

The trends of remembering different OSMOSE elements appears same in the above graphs where one graph represents responses after 7 days and other represents responses when asked immediately after their OSMOSE experience. In both cases, "tree" is the most remembered object and the pond is the least seen object. The only differences are "Forest" and "other" objects seen by HMD participants. After 7 days, they remembered seeing forest, but the participants of "Comprehensibility Study of OSMOSE" were lesser in number to, mention "Forest" as they do not consider bunch of leaves as a forest. Other objects seen by most of the participants of "Comprehensibility Study of OSMOSE" were the light sources or bulbs as they named them, but HMD participants didn't remember these other objects after 7 days.

When asked about the colors they remember seeing in OSMOSE, green and white remain the dominant colors. The interesting observation is about "Red" where the participants of HMD study didn't remember seeing red color in OSMOSE.

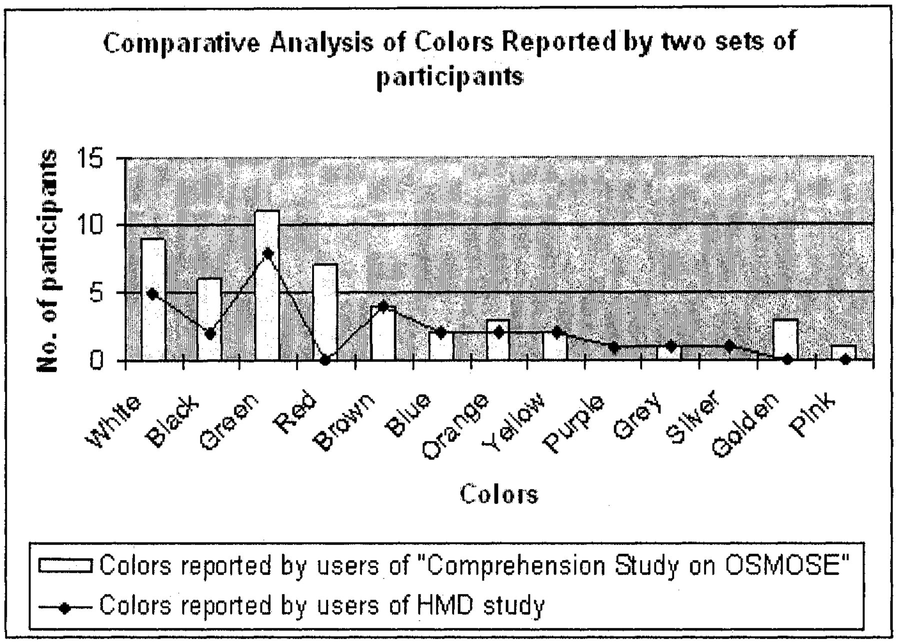


Fig. 5. 14 Results about remembering colors in OSMOSE

These comparisons give us an idea about representations of which objects and colors really went into the "long term memory" of the "HMD study" participants.

Appendix B - Details of "Comprehensibility Study of ADN-Viewer"

In this appendix, we provide some important aspect of this study which is not mentioned in Chapter 6. "Comprehensibility Study of ADN-Viewer" also used the same usability testing process mentioned in Appendix A.

"PLAN" - Roles and Responsibilities:

Rules for coach/observer:

Coaching Session: **5 Mins**

1. Explain the user's guide
2. Describe the instructions
3. Solve user's doubts

Task scenarios session: **10 Mins**

1. During the task, give help only about key controls
2. Can explain the task steps, if user doesn't understand the document.
3. No help for performing the task
4. No hints to perform the task

Role of Remote Viewer:

1. Note down the times to start and end the tasks
2. Enter the tags for criteria which will require observations
3. Enter observations that are important

Role of System Expert:

1. Turn on the projector and adjust it to get the right sharp projection.
2. Keep track of the software during the test session.

DATA COLLECTION

1. Camcorder connected to Assia to record the screen + user
2. Web cam connected to Assia to record the viewer's expressions
3. Wireless microphone connected to Assia to record the voice

"DESIGN" – Preparing Test Documents

The documents that are prepared for the test as presented in the following order:

- ADN-Viewer User Guide
- Consent Form
- User Evaluation
- Task 1 Document
- Post-Task 1 Questionnaire
- Task 2 Document
- Post Task 2 Questionnaire
- Post-test questionnaire

Interact with a DNA Sequence

Action	Keys
Full window display	[CTRL] + [f] to turn on/off
Composite View	[f] to turn on/off
Rotate	arrow keys OR click, hold and rotate using Left Mouse Button
Move	click, hold and drag using Right Mouse Button
Zoom	Click and hold scroll button by moving mouse up and down
Reset view	[CTRL][r]

Stereoscopic View of DNA sequence

Action	Keys
3D (stereoscopic) viewing	[SHIFT] + [s] to turn on/off

View Multiple DNA sequences

Action	Keys
Open file	[CTRL]+[o]
Select sequences in "open file" dialog box	[CTRL] + left mouse click
Add sequence	Menu File, item Add
Select ALL (using bounding box)	[d] to turn on/off

View Genes in a DNA sequence

Action	Keys
Highlight gene (in yellow)	[g] to turn on/off
Gene Names (need to highlight genes first)	[CTRL] + [F2] to turn on/off
Focus	Hover over sequence with mouse to see bounding box Zooming onto a gene – one click with left mouse button Zooming back out – [Esc] – (required to view another gene)

Informed Consent to Participate in Research

This is to state that I agree to participate in a joint research study on the Comprehension and Usability of Immersive Environments, and their application in Bioinformatics conducted at the Department of Computer Science and Software Engineering, Concordia University. The main researchers are: Dr. Ahmed Seffah, Human-Centered Software Engineering Group, Concordia University and Dr. Rachid Gherbi, with the LIMSI-CNRS Lab at the University of Paris-Sud XI, who is visiting Concordia University for the summer term.

A. Purpose of the Study

I have been informed that the purpose of the research is to evaluate ADN-Viewer, a software tool developed at the LIMSI-CNRS lab (France, University of Paris-Sud XI). ADN-Viewer is a software tool that offers 3D visualization of the naked DNA on genomic and comparative genomic scales. ADN-Viewer uses a DNA sequence represented in the form of text as well as a conformational model of 3D structure of naked DNA. It provides a three-dimensional representation of the DNA sequence. This 3D representation is used to visualize the 3D sequence in genomic, genic and atomic modes. For the usability study, only the genomic visualization will be considered.

In addition, as part of a follow-up study, I will be asked to evaluate the NCBI site and/or its associated prototype.

B. Procedures

Dr. Seffah and his team (seffah@cs.concordia.ca, phone 514-848-2424 ext. 3024) are in charge of the study. The study is designed to ask bioinformaticians and biologists about their experiences using the ADN-Viewer and the NCBI site. You will be asked to answer questionnaires and to accomplish a certain number of tasks using the ADN-Viewer. In addition, you will be asked to either accomplish a certain number of tasks and/or to comment on the NCBI site. This should take no more than 40 minutes of your time.

We anticipate no risk to you as a result of your participation in this study other than the inconvenience of the time to complete the questionnaire and to use the ADN-Viewer. While there may be no immediate benefit to you as a result of your participation in this study, it is hoped that we may gain valuable information about your experiences using ADN-Viewer so that we can help improve its usefulness and usability.

All provided information and data collection will be stored anonymously in a database, with no information that can identify participants. Results from the survey will be reported only in aggregate form in scientific communications like articles, workshops, and conference presentations. A summary of the results will be posted on the project Web site (http://rana.cs.concordia.ca/www/co-drive).

If you wish to receive the results of this study, please check the box below and provide an e-mail address.

Name: ....
☐ **Mail address**: ....

C. Conditions of Participation

- I understand that I am free to withdraw my consent and discontinue my participation at anytime without negative consequences.
- I understand that my participation in this study is CONFIDENTIAL (i.e., the researcher will know, but will not disclose my identity)
- I understand that the data from this study may be published.

I HAVE CAREFULLY STUDIED THE ABOVE AND UNDERSTAND THIS AGREEMENT. I FREELY CONSENT AND VOLUNTARILY AGREE TO PARTICIPATE IN THIS STUDY.

NAME (please print) ____

SIGNATURE ____

If at any time you have questions about your rights as a research participant, please contact Adela Reid, Research Ethics and Compliance Officer, Concordia University, at (514) 848-7481 or by email at areid@alcor.concordia.ca.

NCBI-ADN Viewer User Evaluation

Thank you for completing this form based on your own background and experiences. All responses will remain anonymous and results will be used solely for research purposes.

Part 1: User Profile

Age: _____ Gender: ☐ Male ☐ Female

What is your first language? ☐ English ☐ French ☐ Other Please specify: _____

What is your field of study? _____

What is your highest level of education? _____

What is your current position/employment? _____

Part 2: Bioinformatics and Biology Knowledge

How many graduate-level Bioinformatics courses have you taken?

☐ None ☐ 1-2 ☐ >2 courses

How would you rate your knowledge of the Biological Sciences?

☐ None ☐ Basic ☐ Intermediate ☐ Advanced

If relevant, how many years have you been working in Bioinformatics or Molecular Biology?

☐ <1 year ☐ 1-3 years ☐ >3 years ☐ Not applicable

Part 3: Computer Experience

How long have you been using computers?

☐ <6 months. ☐ <1 year ☐ 1-3 years ☐ >3 years

How long have you been using the internet?

☐ <6 months. ☐ <1 year ☐ 1-3 years ☐ >3 years

How would you rate your knowledge of Information Technology and Computer Science?

☐ None ☐ Basic ☐ Intermediate ☐ Advanced

Part 4: Application Experience

How long have you been using the NCBI (National Center for Biotechnology Information) website?

☐ Never ☐ only 1-2 times ☐ <6 months. ☐ <1 year ☐ 1-3 years ☐ >3 years

If relevant, what are the three main tasks you perform on the NCBI site?

1.
2.
3.

If relevant, how would you rate your experience with different Bioinformatics tools?

☐ None ☐ Basic ☐ Intermediate ☐ Advanced

Have you ever tried a virtual reality or 3D environment?

☐ No ☐ Yes

Have you ever used any 3D Bioinformatics Visualization tool?

☐ No ☐ Yes If yes, which one(s) and for what purpose? _____

Have you worked with textual sequences?

☐ No ☐ Yes

Is 3D structure of biological sequences important for you?

☐ Yes ☐ No If yes, why? _____

If relevant, what kind of 3D structures have you worked with? (ex: Software Model or Physical Model)

_____

Part 5: Goals and Activities

What are some of your personal and professional goals?

_____

Describe briefly a typical day at the office or lab (if relevant, include your interaction with Bioinformatics tools)

_____

Please list some of your hobbies and interests below:

_____

Task 1

Goal

Group a set of sequences according to the similarity in their 3D structures, more specifically, their trajectories.

How?

1. From the *file explorer window*, load and display a set of sequences from folder "/sequences/Task_1"
2. (Refer to "View Multiple Sequences" in User Guide)
3. All the sequences are displayed at the same place.
4. Your job is to group similar sequences at one location in space.
5. At the end, all sequences must be placed in a way that sequences in one group have similar 3D trajectories.

Can you please answer the following questions about Task 1?

(Note: ratings are on the scale 1-5, 1 is for the lowest and 5 is for the highest rating)

12. **Can you conveniently see all the sequences together?**

☐ Yes ☐ No

13. **Can you compare all the 3D sequences with each other?**

☐ Yes ☐ No

14. **How important is it to compare such set of sequences for their similar 3D trajectories?**

☐ 1 (Not at all) ☐ 2 ☐ 3 ☐ 4 ☐ 5 (Essential)

15. **What were the criteria you used to group the sequences?**

____

____

____

Task 2

Goal

Find a pair of genes which are spatially close to each other but are far in textual sequences.

How?

1. From the *file explorer window*, double click on "Database"
2. Double click on "**Saccharomyces_cerevisiae_1**" with 230207 number of base pairs
3. Use instructions from user guide to interact with the sequence
4. In a space given below, write names of a pair of genes that are close to each other in space, but if you consider the textual sequence; they are far from each other.

   Pair of genes:

1. ________________ and ________________

2. ________________ and ________________

Can you please answer following questions about Task 2?
(Note: ratings are on the scale 1-5, 1 is for the lowest and 5 is for the highest rating)

1. **If you have worked with DNA 3D structures before, is this 3D DNA representation consistent with what you have seen before?**

   ☐ Yes ☐ No

2. **Is it important to see ALL the gene names at the same time?**

   ☐ 1 (Not at all) ☐ 2 ☐ 3 ☐ 4 ☐ 5 (Essential)

3. **When you view the entire sequence, can you read all the gene names?**

   ☐ 1 (Not at all) ☐ 2 ☐ 3 ☐ 4 ☐ 5 (Definitely Yes)

4. **How would you rate this feature to view the gene names?**

   ☐ 1 (Poor) ☐ 2 ☐ 3 ☐ 4 ☐ 5 (Excellent)

5. **How would you rate the color scheme used to show genes and inter-genes regions?**

   ☐ 1 (Poor) ☐ 2 ☐ 3 ☐ 4 ☐ 5 (Excellent)

)

6. **Enable the classical view. How would you rate the classical view with top, front, side and perspective views in one screen?**

   ☐ 1 (Poor) ☐ 2 ☐ 3 ☐ 4 ☐ 5 (Excellent)

7. **Is it important to see such classical view of a DNA trajectory?**

   ☐ 1 (Not at all) ☐ 2 ☐ 3 ☐ 4 ☐ 5 (Essential)

8. **What is the quality of 3D effect without glasses?**

   ☐ 1 (Poor) ☐ 2 ☐ 3 ☐ 4 ☐ 5 (Excellent)

9. **What is the quality of 3D effect with glasses?**

   ☐ 1 (Poor) ☐ 2 ☐ 3 ☐ 4 ☐ 5 (Excellent)

10. **How frequently would you like to use glasses?**

    ☐ 1 (Will never use glasses)

    ☐ 2 (will use glasses very few times)

☐ 3 (will keep switching between the two)

☐ 4 (will use glasses more often)

☐ 5 (will always use glasses)

11. Which option does you like the most for the 3D viewing?

☐ Normal monitor without glasses

☐ Normal monitor with glasses

☐ Wall projection without glasses

☐ Wall projection with glasses

12. When you zoom-in to one gene in a sequence, can you see the context (neighborhood) of this gene?

☐ Yes ☐ No

13. Is it important for you to see the context (neighborhood) of this gene?

☐ 1 (Not at all) ☐ 2 ☐ 3 ☐ 4 ☐ 5 (Essential)

14. How comfortable is it to see the neighborhood of any one gene?

☐ 1 (Poor) ☐ 2 ☐ 3 ☐ 4 ☐ 5 (Excellent)

Thank you for participating in the study!

ADN-Viewer Post Test Questionnaire

Can you please fill in your answers for the following questions? This summarizes your views about *ADN-Viewer*.

(Note: ratings are on the scale 1-5, 1 is for the lowest and 5 is for the highest rating)

1. **What mouse action would you choose to suggest that you want to go forward and backward?**

   Go Forward: ______________________________

   Go Backward: ______________________________

2. **What mouse action would you choose to suggest that you want to rotate around the sequence?**

   ____

3. **How comfortable is it to explore the DNA 3D structure?**

   Going forward:

   ☐ 1 (Not at all) ☐ 2 ☐ 3 ☐ 4 ☐ 5 (Excellent)

   Going backward:

   ☐ 1 (Not at all) ☐ 2 ☐ 3 ☐ 4 ☐ 5 (Excellent)

   Going up:

   ☐ 1 (Not at all) ☐ 2 ☐ 3 ☐ 4 ☐ 5 (Excellent)

   Going down:

   ☐ 1 (Not at all) ☐ 2 ☐ 3 ☐ 4 ☐ 5 (Excellent)

   Going around:

   ☐ 1 (Not at all) ☐ 2 ☐ 3 ☐ 4 ☐ 5 (Excellent)

4. **How would you rate the feature of zooming-in to one gene in a 3D structure, when clicked?**

   ☐ 1 (Poor) ☐ 2 ☐ 3 ☐ 4 ☐ 5 (Excellent)

5. **Is it useful to have such zooming to see one gene structure from close?**

☐ 1 (Not at all) ☐ 2 ☐ 3 ☐ 4 ☐ 5 (Essential)

6. **Did you notice the "start" and "end" of the sequence?**

☐ Yes ☐ No

7. **Is it important to see "start" and "end" of the 3D DNA structure?**

☐ 1 (Not at all) ☐ 2 ☐ 3 ☐ 4 ☐ 5 (Essential)

8. **Is it sufficient to have "start" and "end" of the structure?**

☐ Yes ☐ No

If No, what else would you like to see to indicate direction?

____

9. **Is there anything unnecessary that you would like to remove from the scene while observing the 3D DNA structure?**

☐ Yes, What is it: ____

☐ No

10. **Do you think system responded to your mouse actions?**

☐ Yes ☐ No

11. **How would you rate the system's response to your actions?**

☐ 1 (Poor) ☐ 2 ☐ 3 ☐ 4 ☐ 5 (Excellent)

12. **Do you think looking at 3D structure in different scales (by zooming in and out) is useful?**

☐ Yes ☐ No

13. What are the obvious things you would like to do to observe any DNA sequence? (check all that apply)

☐ See the Genes in it

☐ See Gene names

☐ See the structure from different angles

☐ See in stereoscopic view / using glasses

☐ See one gene in close-up

☐ See the sequence in all classical views (top, front, side, and perspective views in one screen)

☐ Other: ____________________

14. How would you rate this feature of looking at the 3D structure in different scales?

☐ 1 (Poor) ☐ 2 ☐ 3 ☐ 4 ☐ 5 (Excellent)

15. Did stereoscopic view improve the observation of 3D structure?

☐ Yes, Explain, How: ____________________

☐ No

16. How much did ADN-Viewer satisfy your expectations?

☐ 1 (Poor) ☐ 2 ☐ 3 ☐ 4 ☐ 5 (Excellent)

17. Is there anything that you did not like about ADN-Viewer?

☐ Yes, what is it: ____________________

☐ No

18. Will this tool be useful in your work?

☐ Yes ☐ No

Thank you! ☺

"SETUP" - Physical Test Environment for ADN-Viewer Study:

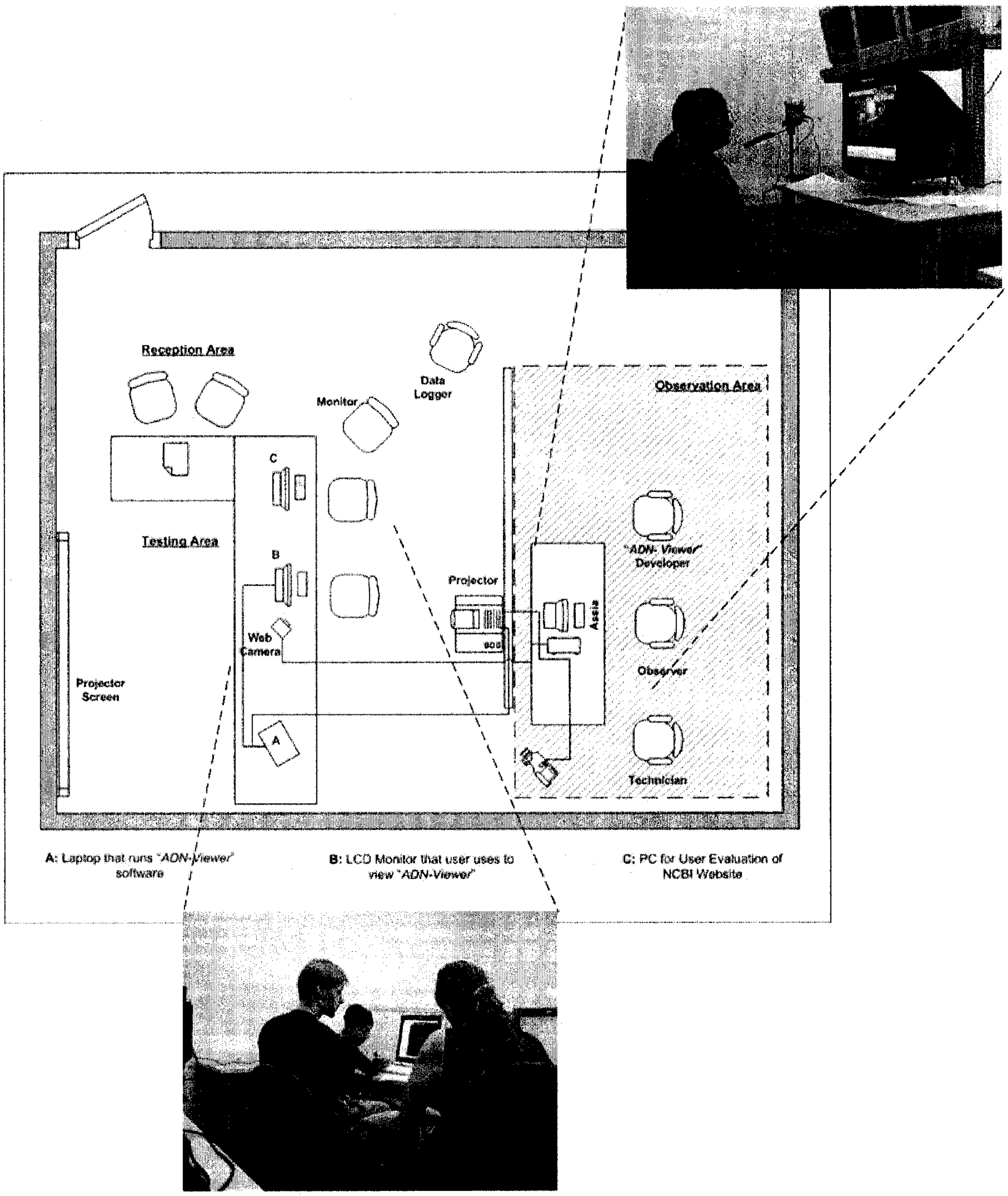


Figure 3B Physical Test Environment for "Comprehensibility Study of ADN-Viewer"

"CONDUCT" and "DEBRIEF" - Conducting the Test Session

- First the "Welcomer" greets the participant at the reception area, asks the participant to read and sign the consent form and introduces him/ her to the monitor of "NCBI website evaluation" test.
- "Monitor" of "NCBI website evaluation test" asks the participant all the user evaluation questions and notes down the answers; then, the first part of the test NCBI website evaluation test" is conducted which is out of scope for this thesis.
- In the second part of this test, "monitor" of "Comprehensibility Study of ADN-Viewer" gives the "User Guide" to the participant and explains how the test will be conducted.
- For first 5-7 minutes, participant tries out all the instructions given in "User Guide" with the help of "ADN-Viewer" developer.
- After this guidance session, "Monitor" gives the first task sheet and explains the goal and the steps to do Task 1. "Monitor" then takes a backseat as participant performs Task 1. Observers note down the user interactions and user's comments. After participant says that he/she finished the task, "monitor" asks participant to fill out some questions related to task 1.
- The same steps are repeated for task 2. Observations and task completion times are noted down and "monitor" asks the participant to fill out answers for some questions related to task 2.
- After the test session, "Interviewer" conducts a brief interview with the participant to ask his/her opinions about ADN-Viewer, in general. "Interviewer" asks every question from post-test questionnaire to the participant and fills out the participants' responses in the questionnaire.
- After the interview session, interviewer presents a small gift as token of team's appreciation towards participant for participating in the study.

"COMPILE" – Summary of User Responses

Here, we present the summary of all the responses for all the questionnaires.

Post Task 1 Question	Responses	Total
Can you conveniently see all the sequences together? **(Contextualization)**	Yes: No:	22 0
Can you compare all the 3D sequences with each other? **(Readability)**	Yes No	19 3
How important is it to compare such set of sequences for their similar3D structures? **(Readability)**	1 2 3 4 5(Essential) Not applicable	7 0 2 4 3 4

Post Task 2 Questions	Responses	Total Score
1. If you have worked with DNA 3D structures before, is this 3D DNA representation consistent with what you have seen before? **(External Visual Consistency)**	Yes No N/A	8 6 8
2. Is it important to see ALL the gene names at the same time? **(Legibility)**	1 2 3 4	3 15 2 2
3. When you view the entire sequence, can you read all the gene names? **(Legibility)**	1 2 3 4 5	2 8 4 3 5
4. How would you rate this feature to show the gene names? **(Legibility)**	1 2 3 4 5	1 6 6 2 7
5. How would you rate the color scheme used to show genes and inter-genes regions? **(Effect of color)**	3 4 5	5 7 10

6. Enable the classical view. How would you rate the classical view with top, front, side and perspective views in one screen? **(Multiple Views)**	1 2 4 5	3 1 13 5
7. Is it important to see such classical view of a DNA structure? **(Multiple Views)**	1 3 4 5 N/A	3 5 5 6 3
8. What is the quality of 3D effect without glasses / stereoscopic view? **(Visual depth cues)**	2 3 4 5	2 7 8 5
9. What is the quality of 3D effect with glasses / stereoscopic view? **(Visual depth cues)**	1 3 4 5	3 3 7 9
10. How frequent would you like to use glasses / stereoscopic vision? **(Visual depth cues)**	1 2 3 5(will always use glasses)	6 2 11 3
11. What option does you like the most? **(Visual depth cues)**	1 (Normal monitor without glasses) 2 (Normal monitor with glasses) 3 (Wall projection without glasses) 4 (Wall projection with glasses)	9 6 4 3
12. When you zoom-in to one gene in a sequence, can you see the context (neighbourhood) of this gene? **(Contextualization)**	Yes No	18 4
13. Is it important for you to see the context (neighbourhood) of this gene? **(Is Contextualization relevant?)**	2 3 4 5 N/A	2 1 7 11 1
14. How comfortable is it to see the neighbourhood of any one gene? **(Contextualization)**	2 3 4 5	4 5 11 2

Post Test Questionnaire	**Responses**	**Total**
1. What mouse action would you choose to suggest that you want to go forward and backward? **(Mappings)**		
Go Forward:	same Scrolling buttons ctrl + scroll button left button	9 10 1 2
Go Backward:	same Scrolling buttons ctrl+scroll left button	12 7 1 2
2. What mouse action would you choose to suggest that you want to rotate around the sequence? **(Mappings)**	same right button	19 3
3. How comfortable is it to explore the DNA 3D structure? **(Navigability)**		
Going forward:	2 3 4 5	2 3 8 9
Going backward:	2 3 4	4 3 6

	5	9
Going up:	2 3 4 5	1 4 8 9
Going down:	2 3 4 5	1 4 8 9
Going around:	2 3 4 5	2 2 5 13
4. How would you rate the feature of zooming-in to one gene in a 3D structure, when clicked? **(Dynamism)**	2 3 4 5	3 9 2 8
5. Is it useful to have such zooming to see one gene structure from close? **(Dynamism)**	3 4 5 N/A	3 4 14 1
6. Did you notice the "start" and "end" of the sequence? **(Directionality)**	Yes	22
7. Is it important to see "start" and "end" of the 3D DNA structure? **(Directionality)**	1 4 5 N/A	3 8 8 1
8. Is it sufficient to have "start" and "end" of the structure? **(Directionality)**	Yes No	7 15
If No, what else would you like to see to indicate direction?	forward or reverse strand, alternative start signs and SMP. no reason mentioned "start" arrow indicating the direction	

	yo want to disable the box to see the 5 prime , 3 prime instead of start and end 3' and 5' instead of start and end. arrow (----→-------→---) small arrow ball at the end an arrow	
9. Is there anything unnecessary that you would like to remove from the scene while observing the 3D DNA structure? **(Simplicity)**	Yes: glasses, just may be closing panel – file explorer No N/A	2 16 1
10. Do you think system responded to your mouse actions? **(Responsiveness)**	Yes No	20 2
11. How would you rate the system's response to your actions? **(Responsiveness)**	3 4 5	3 5 14
12. What are the obvious things you would like to do to observe any DNA sequence? (check all that apply) **(Intuitiveness)**	See gene in it See Gene names See the structure from different angles See in stereoscopic view / using glasses See one gene in close-up See the sequence in all classical views (top, front, side and perspective views in the screen) Other: information about its protein interacts	10 14 12 5 14 3 8

	to see in what angles you are looking at the structure zoom in and out, rotate, move etc. if that gene is attached, how that would affect the neighbourhood of that gene ?(which one is close-by) N/A	 1
13. Did stereoscopic view improve the observation of 3D structure? **(Depth Perception)**	Yes No	13 7
14. How much did ADN-Viewer satisfy your expectations?	4 5 No expectations	8 6 6
15. Is there anything that you did not like about ADN-Viewer?	Yes No	16 4
16. Will this tool be useful in your work?	Yes No N/A	7 12 1

"ANALYSE" – Summary of User Comments:

The main analysis and report is presented in Chapter 6. Here, we first list actual user comments referred in section 5.6 categorized according to relevant comprehensibility criteria. Then, we present some additional descriptive statistics about the collected questionnaire responses.

Clustering:

Responses from expert users:

- Shape
- The similar 3D structure such as loops, curves, sheets etc.
- Global shape (1D, 2D, or 3D), compactness

Responses from intermediate users:

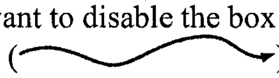
- Make them flat with screen, as flat as possible and group them together

- Similar 3D profile looking at number of bendy and radius of curvature.
- Form, trajectory, size
- Shape
- Shape

Responses from novice users:

- I broke each of sequence into segments (mentally) and tried to see the similarities in them. So the idea is that all sequences arranged (start→ end) on screen and I rotate to get proper view.
- Basically, I tried to match the curves.
- The form (Flat "C", Compact, Important 3D component)

Directionality

- Forward or reverse strand, alternative start signs and SMP.
- Small arrow ball at the end
- 3' and 5' instead of start and end.
- An arrow
- "Start" arrow indicating the direction
- You want to disable the box to see the 5', 3' instead of start and end
- Arrow ()

Additional Descriptive Statistics:

Liking ADN-Viewer:

Overall, when asked whether there is anything they did not like about ADN-Viewer, majority of the participants had some point to mention. The main reasons are names, rotating by mouse, and one participant mentioned that "(one) cannot realize what information it can give".

Comparative analysis

The developers of the ADN-Viewer claimed that use of glasses increases the illusion of stereoscopic vision. When asked about the effectiveness of glasses, we got the following responses.

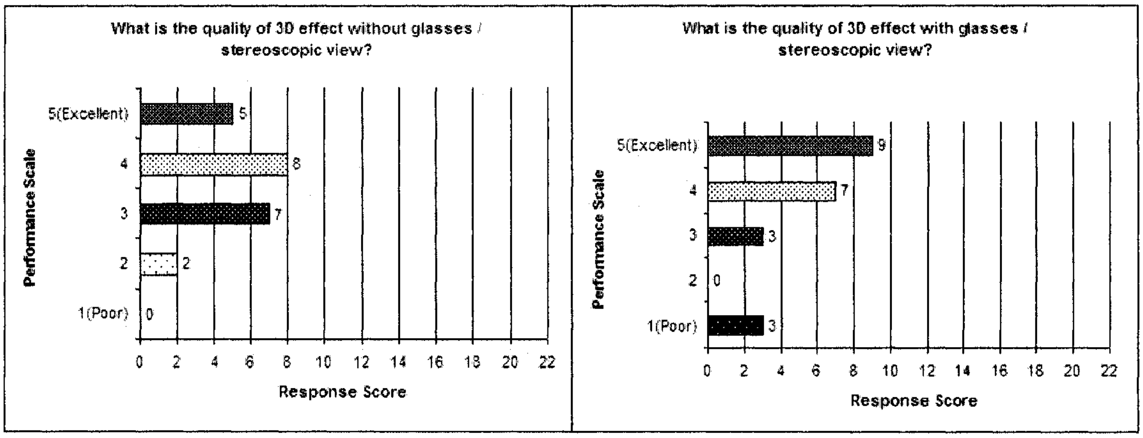


Fig. 6. 20 Comparison of the ADN-Viewer Performance with and without glasses

From the summarized responses, we can see that there is positive increase of excellent ratings, but along with that, there is some increase in the "poor" score also. This may be due the fact that glasses are easier and low-priced in nature and they do not fit well on all the participants' ears. Hence, there is a need to investigate more on this aspect in future ADN-Viewer studies that how shutter glasses affects the depth perception in future ADN-Viewer study.