

**INTERACTION TECHNIQUES FOR COMMON TASKS IN
IMMERSIVE VIRTUAL ENVIRONMENTS**
DESIGN, EVALUATION, AND APPLICATION

A Thesis
Presented to
The Academic Faculty

by

Douglas A. Bowman

In Partial Fulfillment
of the Requirements for the Degree
Doctor of Philosophy in Computer Science

Georgia Institute of Technology
June 1999

**INTERACTION TECHNIQUES FOR COMMON TASKS IN
IMMERSIVE VIRTUAL ENVIRONMENTS**
DESIGN, EVALUATION, AND APPLICATION

Approved:

Larry F. Hodges, Chairman

Gregory Abowd

Albert N. Badre

Elizabeth T. Davis

Jarek Rossignac

Date Approved: _____

ACKNOWLEDGMENTS

The author would like to thank the following people for their help and advice:

- His advisor, Dr. Larry F. Hodges
- The members of the thesis committee: Dr. Gregory Abowd, Dr. Albert Badre, Dr. Elizabeth Davis, and Dr. Jarek Rossignac
- David Koller for his work on the viewpoint motion control experiments
- Dr. Jean Wineman, Brian Wills, and Don Allison for their work on the VR Gorilla Exhibit
- Donald Johnson for his work on the testbed evaluations and the final version of the Virtual Habitat
- Mark Mine, Richard Stoakley, Jeff Pierce, Andrew Forsberg, Ken Hinckley, Matthew Conway, Barry Peterson, Ivan Poupyrev, Ernst Kruijff, Joseph LaViola, and Ben Watson for various collaborations and discussions
- The members of the 3D UI mailing list
- Drew Kessler for help with the SVE toolkit
- The Virtual Environments group at Georgia Tech
- The numerous experimental subjects who volunteered their time
- Dawn Bowman

TABLE OF CONTENTS

Introduction.....	1
1.1 Motivation	1
1.2 Definitions.....	4
1.3 Problem Statement.....	6
1.4 Scope of the Research.....	7
1.5 Hypotheses.....	8
1.6 Contributions.....	9
1.7 Summary of This Work.....	9
1.8 Summary of Recommendations.....	10
1.8.1 Generic VE Interaction Guidelines	10
1.8.2 Guidelines for the Design of Travel Techniques.....	10
1.8.3 Guidelines for the Design of Selection Techniques.....	10
1.8.4 Guidelines for the Design of Manipulation Techniques.....	10
Interaction in Virtual Environments.....	12
2.1 Human-Computer Interaction Concepts	12
2.2 Three-Dimensional User Interfaces.....	14
2.3 Perceptual and Cognitive Psychology Concepts.....	15
2.4 Evaluation of Immersive Virtual Environments.....	16
Design and Evaluation Concepts.....	18
3.1 Taxonomy and Categorization	18
3.2 Guided Design	20
3.3 Performance Measures.....	21
3.4 Range of Evaluation Methods.....	21
3.5 Testbed Evaluation	22
3.6 Models of Human Performance.....	23
3.7 Application of Results.....	23
3.8 Summary of Methodology.....	24
Travel.....	26
4.1 Introduction and Definitions.....	26
4.2 Related Work.....	26
4.3 Original Evaluation Framework.....	27
4.3.1 Categorization of Techniques	27
4.3.2 Performance Measures.....	29
4.4 Initial Experiments.....	30
4.4.1 Spatial Awareness Experiment.....	31
4.4.2 Absolute Motion Experiment.....	32
4.4.3 Relative Motion Experiment.....	32
4.5 Expanded Evaluation Framework	33
4.5.1 Task Characteristics	34

4.5.2 Environment Characteristics.....	34
4.5.3 User Characteristics	35
4.5.4 System Characteristics	36
4.5.5 Information Gathering Experiment.....	36
4.5.5.1 Method.....	37
4.5.5.2 Results	41
4.5.5.3 Discussion.....	42
4.6 Alternate Evaluation Framework.....	43
4.6.1 Taxonomy	43
4.6.2 Guided Design	44
4.6.3 Spatial Orientation Experiment.....	46
4.6.3.1 Method.....	48
4.6.3.2 Results	50
4.6.3.3 Discussion.....	54
4.7 Travel Testbed	56
4.7.1 Method.....	56
4.7.2 Results	61
4.8 Summary	66
Selection and Manipulation.....	67
5.1 Introduction and Definitions.....	67
5.2 Related Work.....	68
5.2.1 Interaction Metaphors	68
5.2.2 Evaluation of Techniques.....	69
5.3 Initial Evaluation and Design.....	70
5.3.1 Techniques Considered	70
5.3.2 User Study	72
5.3.3 HOMER Technique	73
5.4 Formal Evaluation Framework.....	75
5.4.1 Categorization of Techniques	75
5.4.2 Performance Measures.....	77
5.4.3 Outside Factors	78
5.4.3.1 Task Characteristics	78
5.4.3.2 Environment Characteristics.....	78
5.4.3.3 User Characteristics	79
5.4.3.4 System Characteristics	79
5.4.4 Guided Design	79
5.5 Selection/Manipulation Testbed.....	80
5.5.1 Method.....	81
5.5.2 Results	82
5.6 Summary	87
Interaction in a real-world VE application.....	88
6.1 Integrating Techniques into an Application: Issues and Challenges	88
6.2 The Virtual Habitat	89
6.2.1 Original VR Gorilla Application	89
6.2.2 Application to Environmental Design Education.....	90
6.2.3 Interaction Requirements	91
6.3 Interaction Design	92

6.3.1 Naïve Interaction Design.....	93
6.3.2 Intermediate Design Iteration.....	95
6.3.3 Final Interaction Design.....	100
6.4 Final Usability Evaluation	101
Conclusions and Future Work.....	104
7.1 VE Interaction Guidelines	104
7.1.1 Generic VE Interaction Guidelines	105
7.1.2 Guidelines for the Design of Travel Techniques.....	105
7.1.3 Guidelines for the Design of Selection Techniques.....	107
7.1.4 Guidelines for the Design of Manipulation Techniques.....	107
7.2 Formal Design & Evaluation Frameworks	108
7.3 Focus on Applications and Usability.....	109
7.4 Future Work.....	109
7.4.1 Automatic Interaction Design and Performance Modeling.....	109
7.4.2 Cross-task Interaction Techniques.....	110
7.4.3 Comparison with Usability Engineering.....	111
7.4.4 Interaction in Other Display Modalities	112
Appendix A: Standard User Questionnaire.....	113
Appendix B: Comfort Ratings Form	115
Appendix C: Complete results of the travel testbed experiment..	116
Appendix D: Complete Results of the Selection/Manipulation Testbed Experiment	118
References	123
Vita.....	132

LIST OF TABLES

Table 4.1 Average Values of Overall Score for Each Tested Treatment Combination in the Information Gathering Experiment; Higher Scores are Better.....	41
Table 4.2 Number of Subjects Observed Using Common Strategies for Each Travel Technique.....	53
Table 4.3 Mean Completion Times (seconds) for Naïve Search Task (Standard Deviation in Parentheses)	62
Table 4.4 Mean Completion Times (seconds) for Primed Search Task, with Targets not Within View from Start Location (Invisible) or In View from Start Location (Visible).....	64
(*normalized times – seconds per 100 meters).....	64
Table 5.1 Mean Manipulation Time Results by Technique from Testbed Evaluation.....	84
(* The linear mapping used in these cases was a one-to-one physical to virtual hand mapping).....	84
Table 5.2 Interaction Between Required Accuracy and Degrees of Freedom for Manipulation Time (seconds).....	85
Table 6.1 Mean Usability Ratings for the Intermediate Virtual Habitat Interaction Design	99
Table 6.2 Mean Usability Ratings (standard deviations in parentheses) for the Final Virtual Habitat Interaction Design	102
(* features changed since the previous iteration).....	102
Table C.1 Results of Primed Search Task	116
Table C.2 Demographic and Comfort Rating Summary	117
Table D.1 Speed Results for Selection Task.....	118
Table D.2 Speed Results for Manipulation Task.....	119
Table D.3 Demographic and Comfort Rating Summary	122

LIST OF ILLUSTRATIONS

Figure 2.1 General Taxonomy Format.....	19
Figure 2.2 Flowchart of Design and Evaluation Methodology.....	25
Figure 4.1 Taxonomy of Travel Techniques for Immersive Virtual Environments.....	28
Figure 4.2 Environment for the Spatial Awareness Experiment	31
Figure 4.3 The Relative Motion Experiment Environment.....	33
Figure 4.4 Outside View of a Three-Dimensional Corridor	38
Figure 4.5 Interior of a Corridor from the Information Gathering Experiment.....	39
Figure 4.6 Example Completed Corridor Map with Four Word/Location Pairs, One Unpaired Location, and Two Unpaired Words	40
Figure 4.7 Alternate Taxonomy for Travel Techniques with Detail on Position Indication Subtask.....	44
Figure 4.8 Route-planning Technique Using Virtual Map and Stylus.....	45
Figure 4.9 Inside View of a Corridor with a Target Object.....	46
Figure 4.10 Views of Four Corridor Types used in the Spatial Orientation Experiment: Top left: 2D, right angles, top right: 2D, non-right angles, bottom left: 3D, right angles, bottom right: 3D, non-right angles.....	48
Figure 4.11 Mean Error in Various Treatment Combinations for Analysis 1 (left) and Analysis 2 (right)	51
Figure 4.12 Mean Time in Various Treatment Combinations for Analysis 1 (left), and Analysis 2 (right)	52
Figure 4.13 Example Obstacles from the Travel Testbed Experimental Environment.....	57
Figure 4.14 Target Object from the Travel Testbed Experimental Environment Including Flag and Required Accuracy Radius.....	58
Figure 4.15 Virtual (top) and Physical (bottom) Views of the Map Dragging Travel Technique.....	60
Figure 4.16 Interaction Between Task Type and Technique for Think Time on Search Tasks	65
Figure 5.1 Mapping Function for the Go-Go Technique: R_T =Physical Hand Distance, R_V =Virtual Hand Distance. Reproduced from (Poupyrev et al, 1996).....	71
Figure 5.2 Stretch Go-Go Technique, with Gauge.....	71
Figure 5.3 Time Sequence of the HOMER Technique	74
Figure 5.4 Taxonomy of Selection/Manipulation Techniques.....	76
Figure 5.5 Example Trial Setup in the Selection/Manipulation Testbed.....	81
Figure 5.6 Interaction of Selection Technique with Object Distance for Selection Time Measure	83
Figure 5.7 Interaction of Selection Technique with Object Size for Selection Time Measure	83
Figure 5.8 Logarithmic Scale Graph of Interaction Between DOFs and Accuracy	86
Figure 6.1 The Virtual Reality Gorilla Exhibit	89
Figure 6.2 Embedded Audio and Text Information in the Virtual Habitat	91

Figure 6.3 Virtual Menus in the CDS System.....	94
Figure 6.4 Constrained Object Manipulation in CDS with Ray-Casting	95
Figure 6.5 Physical Devices used in the Virtual Habitat Application	96
Figure 6.6 User's View of the Interface Tablet in the Virtual Habitat	97
Figure 7.1 Example Taxonomy and Technique Components: If Performance Results for Techniques A, B, and C are Known, the Performance of Technique D can be Inferred.....	110
Figure 7.2 Simplified Taxonomies Linked Together by Cross-Task Techniques.....	111

SUMMARY

Human-Computer Interaction (HCI)* in three dimensions is not well understood, and there are few 3D applications in common use. Moreover, the complications of 3D interaction are magnified in immersive virtual environment (VE) applications: characteristics such as inaccurate tracking and lack of access to traditional input devices cause the design of user interfaces (UIs) and interaction techniques (ITs) for immersive VEs to be extremely difficult. Despite these difficulties, we maintain that there are complex applications for which immersive VEs are desirable, so special attention needs to be paid to the design and implementation of ITs for these applications.

A large percentage of interactions that take place in immersive VEs fall into a small number of general categories, which include travel (movement of the user's viewpoint from place to place), selection (indicating virtual objects within the environment), and manipulation (setting the position and/or orientation of virtual objects). Given techniques with good performance characteristics for these three interactions, a large number of complex and effective VE applications could be built. In this research we studied ITs for these three universal tasks in the context of a formal, systematic framework, including the design of novel ITs and empirical, comparative evaluations of techniques.

This thesis presents several important results of the use of this methodology. First, we have developed new ITs perform well in a variety of application scenarios. Second, we have designed general testbeds for IT evaluation that may be reused for future performance comparisons. Third, we have obtained a large set of empirical results regarding the performance of ITs. These results led to general principles and guidelines (section 7.1) that can be applied to VE systems to improve performance. Finally, we validated these results by applying them to a real-world VE application, and showing that its usability was measurably improved as a direct result. The results presented in this thesis should be useful and important to anyone developing a VE system with even a moderate amount of interaction complexity.

* For precise definitions of this and other key terms, see section 1.2.