The Role of Rest Frames in Vection, Presence and Motion Sickness

by

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Date
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Abstract

The Role of Rest Frames in Vection, Presence and Motion Sickness

by Jerrold D. Prothero

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Industrial Engineering

A framework is presented for comprehending partly participants’ spatial perception in virtual environments. Specific hypotheses derived from that framework include: simulator sickness should be reducible through visual background manipulations; and the sense of presence, or of “being in” a virtual environment, should be increased by manipulations that facilitate perception of a virtual scene as a perceptual rest frame. Experiments to assess the simulator sickness reduction hypothesis demonstrated that congruence between the visual background and inertial cues decreased reported simulator sickness and per-exposure postural instability. Experiments to assess the presence hypothesis used two measures: self-reported presence and visual-inertial nulling. Results indicated that a meaningful virtual scene, as opposed to a random one, increased both reported presence and the level of inertial motion required to overcome perceived self-motion elicited by scene motion. The simulator sickness research implies that visual background manipulations may be a means to reduce the prevalent unwanted side-effects of simulators. The presence research introduces a procedure, possibly based on brain-stem level neural processing, to measure the salience of virtual environments. Both lines of research are central to developing effective virtual interfaces which have the potential to increase the human-computer
bandwidth, and thus to partially address the information explosion.
# TABLE OF CONTENTS

List of Figures .................................................. iv
List of Tables .................................................. v
Glossary .......................................................... vii
Preface ........................................................... xiv

## Chapter 1: Introduction ........................................... 1
1.1 Overview ...................................................... 1

## Chapter 2: Literature Review .................................... 3
2.1 Introduction ................................................... 3
2.2 Introduction to Presence ....................................... 3
2.3 Area I: Presence Measures .................................... 5
2.4 Area II: Presence Manipulations ............................... 14
2.5 Area III: Motion Sickness ..................................... 23

## Chapter 3: Introduction to the Research ......................... 26
3.1 Introduction .................................................... 26
3.2 The Rest Frame Construct ..................................... 26
3.3 Implications of the Rest Frame Construct ..................... 28
3.4 Division of the Research ...................................... 37
3.5 Guide to the Experiments ..................................... 38
Chapter 4:  Area I: Presence Measures

4.1 Introduction .................................................. 55
4.2 General Methods .............................................. 58
4.3 Experiment AIE1: Narrow Field-of-View (Reported Presence) . . . . 67
4.4 Experiment AIE2: Meaningful/Random .......................... 73

Chapter 5:  Area II: Presence Manipulations

5.1 Introduction .................................................. 84
5.2 Experiment AIIIE1: Foreground Occlusions and Reported Presence I . 85
5.3 Experiment AIIIE2: Foreground Occlusions and Reported Presence II 89
5.4 Inside-Out Displays and Foreground Occlusions ...................... 92

Chapter 6:  Area III: Motion Sickness

6.1 Introduction .................................................. 93
6.2 Experiment AIIIE1: Independent Visual Background for Low-End Systems I ............................................. 94
6.3 Experiment AIIIE2: Independent Visual Background for Low-End Systems II ............................................. 100
6.4 General Discussion ............................................. 108

Chapter 7:  General Discussion

7.1 Introduction .................................................. 110
7.2 Area I: Presence Measures ..................................... 110
7.3 Area II: Presence Manipulations ................................ 114
7.4  Area III: Motion Sickness ................................. 115
7.5  Selected Rest Frames and Cognition ..................... 116

Chapter 8:  Future Research ................................. 119

8.1  Introduction ........................................... 119
8.2  Area I: Presence Measures ............................... 119
8.3  Area II: Presence Manipulations .......................... 122
8.4  Area III: Motion Sickness ............................... 123

Chapter 9:  Conclusion ........................................ 124

9.1  Overview .............................................. 124

Bibliography .................................................. 126

Appendix A:  CogE1: The Influence of Meaning on Presence

Appendix B:  Area I Pilot Studies: Visual-Inertial Nulling Presence Measures

B.1  Initial Pilot Studies ..................................... 141
B.2  Pilot Studies Related to Experiment AIE1 ............... 144

Appendix C:  Area II Pilot Studies: Foreground Occlusions

C.1  Foreground Occlusions Increase Presence ............... 148
C.2  Inside-Out Display Pilot Studies ........................ 149

Appendix D:  Area III Pilot Studies: Motion Sickness

Appendix E:  Foreground Occlusions and Binocular Rivalry

Appendix F:  Simulator Sickness Terminology
Appendix G:  Simulator Sickness Questionnaire
LIST OF FIGURES

2.1 Foreground Occlusion ............................................. 15
2.2 Inside-Out and Outside-In Roll Representations ................. 20
3.1 Presence Measure Experimental Configuration .................. 42
3.2 Independent Visual Background (IVB) ........................... 43
3.3 Rotating Chair ...................................................... 47
C.1 Inside-Out Display Pitch Representations ........................ 154
## LIST OF TABLES

3.1 Dissertation Experiments .......................... 40

4.1 Experiment AIE1: Field-of-View (Reported Presence) ........ 68
4.2 Participant Overview for Experiments AIE1 .................. 69
4.3 Reported Presence Data for Experiment AIE1 ................. 71
4.4 Experiment AIE1 ANOVA Table for Reported Presence Data .... 72
4.5 Experiment AIE2: Meaningful/Random (Nulling Measure) .... 75
4.6 Participant Overview for Experiment AIE2 .................. 76
4.7 Nulling and Reported Presence Data for Experiment AIE2 .... 78
4.8 Experiment AIE2 ANOVA Table for Cross-Over Data .......... 79
4.9 Experiment AIE2 ANOVA Table for Reported Presence Data ... 80
4.10 Correlations Between EFT Scores and the Two Dependent Measures 80

5.1 Experiment AIIIIE1: Foreground Occlusions and Reported Presence I . 86
5.2 Participant Overview for Experiment AIIIIE1 .................. 87
5.3 Experiment AIIIIE2: Foreground Occlusions and Reported Presence II 90
5.4 Participant Overview for Experiment AIIIIE2 .................. 91

6.1 Experiment AIIIIE1: Independent Visual Background I (Low-End) .. 95
6.2 Participant Overview for Experiment AIIIIE1 .................. 96
6.3 Data From Experiment AIIIIE1 ............................. 99
6.4 Experiment AIIIIE2: Independent Visual Background II (Low-End) . 102
6.5 Participant Overview for Experiment AIIIIE1 .................. 103
<table>
<thead>
<tr>
<th>Section</th>
<th>Title</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>6.6</td>
<td>Data From Experiment AIIIE2</td>
<td>106</td>
</tr>
<tr>
<td>B.1</td>
<td>Cross-Over Data for Experiment AIP3</td>
<td>146</td>
</tr>
<tr>
<td>B.2</td>
<td>Cross-Over Data for Experiment AIP4</td>
<td>147</td>
</tr>
<tr>
<td>G.1</td>
<td>Computation of SSQ Scores</td>
<td>165</td>
</tr>
</tbody>
</table>
GLOSSARY

ANCHOR EFFECT: The psychological phenomenon whereby different starting points yield different estimates, which are biased towards the initial values.

AREA I: As used in this dissertation, the line of research which seeks to measure the sense of presence in a virtual environment in terms of the degree to which the selected rest frame is influenced by the virtual environment.

AREA II: As used in this dissertation, the line of research which seeks to manipulate the sense of presence in a virtual environment by altering the selected rest frame.

AREA III: As used in this dissertation, the line of research which seeks to reduce simulator sickness by reducing the disagreement between the rest frames implied by visual and vestibular cues.

ATAXIA: Lack of muscular coordination. Used in this document to indicate postural instability.

CI: Content-of-interest.

CLASS A MEASURES: In Brindley’s definition [15], psychological measures which can be expressed solely in terms of a comparison of sensory stimuli. Stated differently, measures in which the participant’s response is expressed in a way which is congruent to the input stimuli. For instance, having a participant
adjust a light intensity until it matches the perceived brightness of another light would be a Class A measure.

CLASS B MEASURES: In Brindley’s definition [15], psychological measures which can not be expressed solely in terms of a comparison of sensory stimuli. Stated differently, measures which require the participant to transform the input into a different form before responding. For instance, magnitude estimation of vection. Magnitude estimation requires the participant to evaluate an impression of self-motion.

CONTENT-OF-INTEREST: The usual scene displayed by a virtual environment. See “independent visual background.”

CROSS-OVER AMPLITUDE: As used in this document, the inertial amplitude at which participants “cross-over” between visual and inertial dominance. That is, between having the sense of self-motion determined by visual or (conflicting) inertial self-motion cues. See “visual-inertial nulling”.

DEMAND CHARACTERISTICS: A situation in which a observer’s response is influenced more by the research setting than by the independent variable.

EFT: Embedded Figures Test.

EMBEDDED FIGURES TEST: A standardized measure of cognitive style and analytical ability. Used in the research described here as a measure of field dependency. (See Section 3.8.2.)

FIELD DEPENDENCE: The degree to which an observer has difficulty analyzing part of an organized field independently of the field.
FIELD-OF-VIEW: The instantaneous angular extent of the virtual scene within the visual field.

FOREGROUND OCCLUSION: An obstruction mounted in front of a display in such a way that only the display (and not its boundary) is visible through the obstruction, and such that the display is at a greater visual distance than all other available visual cues.

FOREGROUND OCCLUSION EFFECT: A psychological or performance change produced by a foreground occlusion.

FOV: Field-of-view.

HITL: Human Interface Technology Laboratory at the University of Washington.

The site for the work described in this dissertation.

HMD: Head-mounted display.

HUMAN FACTORS: The study of human capabilities and limitations as they pertain to the design of tools and environments.

IMMERSIVE: A system which displays information to a large percentage of human sensory channels, and which additionally may accept commands from a wide range of human motor output.

INDEPENDENT VISUAL BACKGROUND: A visual scene made to appear behind the content-of-interest of a virtual environment, and controlled independently of the content-of-interest. Used to reduce motion sickness.
INDUCED MOVEMENT: The apparent motion of a stimulus caused by motion of nearby stimuli.

INERTIAL DETECTION THRESHOLD: The amplitude of inertial motion at which it is just possible to detect the movement.

INTERFACE SICKNESS: The component of simulator sickness which results from an imperfect simulation, for instance due to lag, poor inter-ocular adjust, poor resolution, etc. (This term is introduced by myself and Mark Draper. For a discussion, see Appendix F.)

INTERFACE STUDIES: The study of the information boundary between systems. It encompasses the interactions between humans, software and hardware.

IVB: Independent visual background.

LUNING: A binocular rivalry effect occurring in HMD’s. If there is a partial overlap between the scenes displayed to the right and left eyes, the nasal edge of the screen for each eye may be perceived as bands in the common visual field. The right and left bands form a “moon-like” enclosure, hence the term “luning”.

MAGNITUDE ESTIMATION: Psychophysical scaling method in which the observer assigns numbers according to the apparent magnitudes of the stimuli.

MOTION SICKNESS: A pattern of symptoms including nausea, headaches and disorientation which result under some conditions from exposure to motion stimuli.

MULTI-MODAL NULLING: The measurement of the effect of stimuli to one sensory modality in terms of perceptual changes observed from a second sensory modality. See “visual-inertial nulling”, a specific case of multi-modal nulling.
PRESENCE: Informally, the sense of “being somewhere”, usually used with respect to the sense of “being in” a computer-generated space. This dissertation suggests a definition in terms of the rest frame construct. See “presence hypothesis.”

PRESENCE HYPOTHESIS: The sense of presence in an environment reflects the degree to which that environment influences the selected rest frame.

PROPRIOCEPTION: The reception of stimuli produced within the organism. Generally used in the context of recognizing the location of or forces on parts of the body.

PSYCHOPHYSICS: The study of the capability of an organism to detect, quantify, or identify a stimulus.

RANGE EFFECT: The psychological phenomenon whereby magnitude estimations are strongly influenced by the range of stimuli to which participants are exposed.

REFERENCE FRAME: A coordinate system with respect to which positions, orientations and motions can be judged.

REST FRAME: The particular reference frame which a given observer takes to be stationary.

REST FRAME CONSTRUCT: The nervous system has access to many rest frames. Under normal conditions, one of these is selected by the nervous system as the comparator for spatial judgments. We call this the “selected rest frame”. In some cases, the nervous system is not able to select a single rest frame.

RFC: Rest Frame Construct.
RT: Reaction-time. Used as a dependent measure in the inside-out display research.

SEE-THROUGH: (In conjunction with HMD’s.) A display in which a virtual image is seen super-imposed on the real environment, for instance by means of projecting the image on a half-silvered mirror.

SELECTED REST FRAME: A rest frame selected by the nervous system from environmental stimuli. See Rest Frame Construct.

SHARPENED ROMBERG: A stance in which a person stands with heel-to-toe, arms folded across the chest and chin up. It is intended to make balance more difficult, and to therefore make more detectable any balance problems.

SIMULATOR SICKNESS: The generic feeling of sickness resulting from exposure to a computer-generated space. (The definition of this term is moderately controversial. For a discussion, see Appendix F.)

SIMULATOR SICKNESS QUESTIONNAIRE: A standard questionnaire and scoring procedure for recording and analyzing reported simulator sickness symptoms [55].

SSQ: Simulator Sickness Questionnaire.

SPATIAL PERCEPTION: The perception of the position, angular orientation and motion both of the observer and of objects external to the observer.

STD: Standard deviation.

TEXTURE MAP: An image, either digitized or synthesized, which is mapped onto a surface.
VECTION: The visually-induced perception of self-motion.

VISUAL-INERTIAL NULLING: A procedure whereby conflicting inertial and visual cues are presented simultaneously. The observers’ responses indicates the extent to which their perception is determined by the visual or the inertial cues. By varying inertial stimulus amplitude, the “point of subjective equality” (crossover between visual and inertial dominance) can be determined. Consequently, the effectiveness of different visual stimuli can be scaled in terms of inertial stimulus amplitude. (This technique is introduced as a presence measure in Chapter 4.)

VIRTUAL ENVIRONMENT: A computer-generated space which is: 1. immersive; and 2. can induce a sense of presence.

VIRTUAL REALITY: A synonym for virtual environment.

VIRTUAL IMAGE: A image which appears to come from a point in space where it does not actually originate.
PREFACE

*How can he possibly be humble? He hasn’t done anything yet.*

— Albert Einstein

This dissertation was motivated by the need to manage complex information. The wealth of the industrial economies is increasingly in the form of information, rather than of physical materials. In the United States, information services have grown relative to the rest of the economy since 1860, with a sharp acceleration after 1940 [53]. For a recent account of the implications of this evolution for the workforce, see Hunt [51]. A monograph surveying the underlying trends, and projecting their social and political implications, can be found in Prothero [79].

A similar evolution affects engineering. Engineering will increasingly be limited less by the properties of materials and more by the complexity of the tasks undertaken. This is because more powerful tools continually tilt the balance of difficulty further from the mechanics of construction and towards design and maintenance. As an indication of where engineering as a whole may be headed, consider the discipline most limited by complexity (and least by physical constraints), software engineering. The centrality of the complexity problem to software engineering is well-understood by its practitioners. According to Gelernter, “If you’re a software designer and you can’t master and subdue monumental complexity, you’re dead: your machines don’t work” [27] (p. 52). Similarly, Fredrick Brooks, in the 1995 update of his classic software engineering book *The Mythical Man-Month* [26], states that “complexity is the business we are in, and complexity is what limits us.” (p. 226; emphasis in the original.)
The frequent examples of complexity-related software failures are often summarized in the Association for Computing Machinery’s *Risks Digest* [6]. In the May 1997 issue, for instance, we read of the 15-month delay in the opening of the “world’s most advanced air-traffic-control centre” as a result of software bugs buried in 1.82 million lines of code [58].

One particularly intricate branch of software engineering, compiler construction, has evolved a mini-mythology to express the complexity problem. Successive editions of “Compilers: Principles, Techniques and Tools” [4] have featured a knight armed with the tools of compiler construction doing battle with a “dragon of complexity”. It is a creature whose hot breath will become increasingly familiar to engineers of all disciplines as we progress into the information age. This dissertation is, in a sense, a joust with the dragon.

It is possible to cleave complexity into two related (and overlapping) areas of research. The first deals with the manipulation of information inside of coherent modules. This is in essence the study of algorithms, the domain of computer science. The other is the flow of information across the boundary of modules: the study of interfaces. As yet, there is no established academic setting for the study of interfaces\(^1\). It incorporates parts of various disciplines, such as: computer science; education; electrical engineering; ergonomics/human factors; industrial engineering; mathematics; psychology; and technical communication. While the general definition of an interface includes the information boundary between any two or more systems, for instance two software or hardware modules, this dissertation is concerned only with the human-computer interface.

Comparing algorithms to interfaces, I suggest that interfaces are in the long run the harder problem. The reason is that complexity is related to uncertainty. The

\(^1\) Note, for instance, that this dissertation was written for a Mechanical Engineering degree.
greatest uncertainty occurs where distinct systems come together (thus losing internal consistency): \textit{i.e.}, at the interface. It follows that the design of effective interfaces is central to confronting the complexity problem in engineering.

It is unfortunate, therefore, that we do not know more about how to design interfaces. The development of an interface for a new problem is guided either by general rules, which provide little precision for the problem at hand \cite{92}, or by usability testing \cite{23}, which has to be repeated for each new interface. At present, interface design is generally a trial-and-error process, with the consequent costs to development time and quality. As the tasks we need to perform become more complex, both the requirements placed on interfaces, and the difficulty of achieving these requirements, will increase.

The (perhaps unattainable) ideal would be to have a mature field of “interface engineering”, which would allow one to systematically construct interfaces with predictable properties, in terms of their ability to convey information both directions across the human-computer boundary. To the extent that such a branch of engineering were achievable, it would augment the current techniques for building interfaces based on general rules, experience, intuition and usability testing.

Engineering (in our case, the hypothetical “interface engineering”) does not strictly require, but does benefit from, an underlying scientific theory which provides a basis for predicting performance. Science in turn requires measures which can be used to accurately assess the outcome of experiments. A goal of this dissertation, therefore, was to investigate measures related to the goodness of interfaces. (For a brief survey of existing interface goodness measures, currently in a rudimentary state of development, see \cite{78}.)

This dissertation focuses on “virtual interfaces”, a somewhat ill-defined term. I choose to define a “virtual interface” as one which has two properties: “sensory
immersion” (meaning that the interface makes use of a large percentage of the human sensory bandwidth); and the ability to induce a sense of “presence”, or of “being in”, an environment implied by the interface\(^2\). There are at least three reasons why the study of virtual interfaces is important. The first reason is that the sensory immersion which is characteristic of virtual interfaces has the potential to increase the human-computer bandwidth, an important point in view of the complexity problem. The second reason is that virtual interfaces will become increasingly common as technology advances. The third reason is that psychologically, virtual interfaces can be easier to study than traditional interfaces, in that by “tricking” the perceptual system virtual interfaces can evoke stronger psychological responses.

The fundamental advantage of virtual interfaces is that, by making better use of natural human sensory inputs, they have the potential to greatly increase the human-computer communication bandwidth. The fundamental disadvantage of virtual interfaces is that (precisely because they can make compelling use of the human perceptual system) virtual interfaces have the capability to cause unwanted side-effects. These side-effects include simulator sickness and postural instability.

Two crucial human factors problems limit the effective use of virtual interfaces. The first problem is the lack of robust measures for how good virtual interfaces are, without which it is difficult to build the knowledge needed for systematic and high-quality interface engineering. The second problem is side-effects. It is suggested here that useful light can be shed on both of these problems (and quite a few others) by a

\(^2\) The use of the word “virtual” in “virtual interface” is related to the term “virtual images” in optics. A virtual image is one which appears to originate from a location which is not physically occupied by the source of the image. For instance, an object seen in a mirror appears to be behind the mirror, but is not \([37]\). Similarly, a virtual interface (or, somewhat more generally, a virtual environment) creates a strong impression that something “really” exists which in fact lacks a physical instantiation.
single, concise framework: the rest frame construct\textsuperscript{3}. The purpose of this dissertation is to introduce the rest frame construct and its applications.

\textsuperscript{3} In prior publications, I have referred to the “rest frame construct” as the “rest frame hypothesis”. The change to “rest frame construct” was made on the recommendation of my doctoral committee, to emphasize that the intent is more to find a convenient summary of the existing literature on spatial perception than to form a testable hypothesis.
ACKNOWLEDGMENTS

This dissertation required the support and guidance of many people. I am pleased to acknowledge their efforts. I hope that the final result is worthy of their involvement.

I would like to thank the members of my supervisory committee: Dr. Thomas Furness (chair), Dr. Linda Brubaker, Dr. Earl Hunt, Dr. Kailash Kapur, Dr. Gregory Miller and Dr. Donald Parker. Dr. Maxwell Wells informally played a similar advisory role, as well as administering the research grant under which most of this work was funded.

I owe additional thanks to Drs. Furness, Hunt, Parker and Wells for providing detailed comments on several drafts of this dissertation. The final version is greatly improved as a result of their involvement. Of course, I must take personal responsibility for remaining flaws.

My research was most influenced by Drs. Furness, Parker and Wells. Together, they provided a truly impressive expertise in perceptual psychology and the human factors of virtual environments. While the framework developed here is primarily of my own devising, it certainly would not have arisen without their insight and support. I owe a particular debt to Dr. Parker for introducing me to the literature on perception, for guidance on the design of the visual-inertial nulling experiments, and for helping to arrange for the loan of a rotating chair from the National Aeronautics and Space Administration (NASA).
While I was the lead investigator for all experiments reported here except Experiment CogE1 in Appendix A, many of these experiments were conducted as collaborations. In particular, Dr. Hunter Hoffman played a very active role in the reported presence foreground occlusion experiments (AIIIP1, AIIIE1 and AIIIE2) and Mark Draper was similarly involved in the “low-end” simulator sickness experiments (AIIIE1, AIIIP1 and AIIIE2). I learned a great deal from both and enjoyed their company.

Joris Groen, a visiting student from Leiden University in the Netherlands, was kind enough to administer Experiment AIIIE2, which followed a double-blind procedure.

A short pilot study (AIIIP2) was conducted using a driving simulator at Hughes Research Laboratories (HRL). This study was done in collaboration with Dr. Wells, and with the assistance of HRL staff. I am particularly grateful to Dr. Peter Tinker of HRL for technical assistance, and to HRL for allowing use of this facility.

Another pilot study was carried out at the University of Washington’s psychology department, with the aid of Dr. Hoffman, Jennifer McLean, and Dr. Geoffrey Loftus. While the study is not reported in this document it did help to guide later research. I thank them for their assistance.

Technical support was of course crucial to all of my dissertation research. I am particularly grateful for the software development of Paul Schwartz. Mr. Schwartz provided working software prototypes for many of the experiments described in this dissertation, which I subsequently enhanced as needed. He showed a remarkable patience, diligence and good humor throughout.

The visual-inertial nulling experiments of Chapter 4 and Appendix B were technically challenging, due both to the inherent difficulties of the design and
due to repeated hardware failures. The electronics expertise of Robert Burstein was often of great use. Others who contributed to the hardware support of these experiments included Chris Airola, Arthur Gonzales, Jaswant Jabal and Herb Kramer.

I am grateful to Toni Emerson and her excellent assistants in the Human Interface Technology Laboratory (HITL) library. Good information is essential to research, and I feel very fortunate to have had access to a research library devoted to virtual interfaces.

This research was conducted at the HITL. While most of the HITL staff were not directly involved in this research, this dissertation would not have been possible without them. Rather than single out individuals, I would like to thank them all for their fine work.

While I am grateful for the assistance of many people from outside of the University of Washington, I would like to acknowledge two in particular. One is Dr. John Jahnke, who visited from the University of Miami in Ohio. Dr. Jahnke suggested having participants indicate the perceived inertial endpoints of their motion in the visual-inertial nulling experiments. This was a great improvement over the technique I had previously tried for measuring visual or inertial dominance. The second is Dr. Robert Patterson of Washington State University, for discussions of binocular rivalry (see Appendix E).

My appreciation also goes out to the numerous experimental participants who, with remarkable good humor, took part in a wide variety of odd experiments.

It is usual in dissertations to acknowledge the friends and family members who one to varying degrees deserted during the Ph.D. process, and who nevertheless provided their unflagging support. I have come to understand why
this tradition arose. Of the many to whom my thanks are due, I mention in particular my fiancee, Rita Solon; my parents, John and Joyce Prothero; my brother, Jeff Prothero; my sister, Jacky Jeffery; and the members of my immediate “chess circle”, Philipp and Vera Frenkel, Drayton Harrison, Ken Plesset and David Zick.

The experiments described in Chapter 4 made use of a rotating chair (Contraves Goerz Co. Direct Drive Rate Table Series 800 and a Neurokinetics, Inc. Motion Simulator Controller). This was graciously loaned to Dr. Parker by NASA.

The Division ProVision 100’s used in Experiments AIIP1, AIIE1 and AIIE2 were acquired as the result of a grant from the U.S. West Foundation to a HITL educational project.

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Finally, I would like to thank the U.S. taxpayers who, whether or not they would approve, have funded the following research.
DEDICATION

To the memory of my grandparents, and to Rita.
Chapter 1

INTRODUCTION

The more closely and precisely one observes particulars, the sooner one arrives at a perception of the whole.

— J.W. Goethe

1.1 Overview

Virtual environments have the potential to increase the human-computer communication bandwidth by mimicking natural human interaction through appropriate stimulation of sensory channels. However, virtual interfaces are confronted with two fundamental problems. The first problem is the lack of robust measures for the quality of interfaces, without which it is difficult to build the knowledge needed for systematic and high-quality interface engineering. The second problem is that, because they effectively stimulate human perceptual systems, virtual interfaces have the capability to confuse the nervous system with unpleasant consequences, including simulator sickness.

It is suggested that a useful (if partial) measure for the quality of an interface is the degree to which it can induce presence. “Presence” refers to the sense of “being in” a computer-generated space. It is characteristic of virtual interfaces that they produce the sense that one is not simply looking at an image, but is instead inside of a space generated by the computer. Manipulations which increase the ease-of-use or
intuitiveness of an interface also tend to increase the sense of presence. Conversely, a good measure for presence should tell us something about the quality of the interface.

There are certainly limitations to presence as a measure for the quality of an interface. It is a general and somewhat ambiguous measure: it does not replace task-specific performance measures. And higher presence is not always a good thing. For instance, if the task requires switching rapidly between two displays, high presence in either may impede a smooth transfer. Nevertheless, presence is an important variable to study in the search for interface goodness measures.

Both presence and simulator sickness deal with complex psychological issues. It is likely that a useful approach to these problems will have to be based on fundamental principles. The approach described in this dissertation is based on an emerging understanding of multisensory spatial perception. This dissertation summarizes a good deal of the literature on spatial perception through the “rest frame construct” (RFC). The RFC suggests that spatial judgments are made with respect to a “rest frame” (definition of what is stationary) which is not physically determined, but which is carefully maintained by the nervous system.

The most important applications of the RFC are to the measurement of presence based on spatial perception and to the reduction of simulator sickness. However, the RFC also predicts that foreground occlusions should affect presence and spatial perception. Research on all of these topics is described.
Chapter 2

LITERATURE REVIEW

*Books are lighthouses erected in the great sea of time.*

— E.P. Whipple

2.1 Introduction

The research in this dissertation is broken into 3 areas: the measurement of presence; effects of foreground occlusions; and simulator sickness. (In the formulation to be introduced in Chapter 3, these three areas correspond respectively to the measurement, manipulation and malformation of selected rest frames.) This chapter summarizes the relevant literature.

Section 2.2 introduces the literature on presence, and suggests why the study of presence may provide a useful (if partial) measure for the quality of an interface. Section 2.3 surveys the literature on psychological measures, in particular as they relate to presence. Section 2.4 reviews effects of foreground occlusions. Finally, Section 2.5 introduces the literature on motion sickness and simulator sickness.

2.2 Introduction to Presence

Informally, “presence” refers to the sense of “being somewhere”: usually in the sense of being in a computer-generated or computer-mediated environment. A possible refinement to this definition, relating presence to the spatial perception literature, will be introduced in Section 3.3.3. The current section reviews what is known about presence and suggests why it may be of importance.
The view that presence is of primary importance to the study of virtual interfaces is not universally held. Ellis points out that increasing presence in one part of a task may decrease global performance (by inhibiting smooth transitions between distinct environments). He states that “the design of a teleoperation or virtual environment system should generally focus on the efficient communication of causal interaction. In this view the sense of presence, that is of actually being at the simulated or remote workplace, is an epiphenomenon of secondary importance for design.” [24]

Nevertheless, presence seems worthy of special attention for the following two reasons. The first reason is that presence is a common property of virtual interfaces. Hence, any attempt to explain the psychology of interfaces must explain presence.

The second reason is that while presence may not be directly related to the effectiveness of an interface, it appears to reflect many things which are. Thus, measuring presence may be a convenient means to assess the importance of these factors. Examples of factors which research implies increase the sense of presence include many which make an interface more natural to use (more intuitive). The literature covers, for instance: interactivity and pictorial realism [108]; update rate [7, 108]; field-of-view (FOV) [36, 82]; head-tracking and stereoscopic cues [39]; spatialized sound [40]; the addition of tactile cues [42]; and the degree to which the content is engaging [75]. Research reported in this dissertation (Appendix A; and at greater length in [41]) suggests that presence is related to the amount of meaning extracted from a display, with all other variables held constant. Presence in a virtual environment may also improve transfer of training to the real world [16].

The degree to which presence can measure the over-all effectiveness of an interface of course depends on the strength of the indirect link between presence and effectiveness. The strength of this link can only be established empirically, by examining cases in which good measures for both presence and over-all effectiveness are available.

Because it appears closely related to the nature and effectiveness of virtual interfaces, presence is a primary focus of this dissertation.
2.3 Area I: Presence Measures

This section gives a background on psychological measures, particularly as they relate to the measurement of presence. It summarizes the literature relevant to the research reported in Chapter 4.

2.3.1 Overview of Psychological Measures

This section conceptually introduces Class A and Class B measures, physiological measures, threshold measures and multi-modal nulling. Applications to the measurement of presence appear in subsequent sections.

A measurement, by definition, requires that one thing be compared with another. Spatial comparisons can be made with respect to a standard unit of distance, such as a meter stick. What are the psychological equivalents of the meter stick?

An important property of a good measure is that it be very direct: that is, that the measure require few transformations of its input. This is because each transformation introduces possible sources of noise. For sensory experiments, Brindley [15] introduced a useful terminology for discussing how direct a psychological measure is. The most direct he termed "Class A" measurements, which can be expressed solely in terms of a comparison of sensations. For instance, a Class A measure for ability to distinguish colors might involve asking an observer to indicate which two of three adjacent colored lights matched each other.

In many cases, Class A psychological measures are not possible. For example (to stick with sensory experiments, for which Brindley developed his terminology) one might be interested in measuring how observers perceive colors to be related to each other. It turns out that humans are comfortable naming the color space with combinations of four (but not three) colors. Across cultures, the preferred colors correspond to "red, yellow, green and blue" [60, 52, 11]. The color naming experiments which determined this preference (and which contributed to the now
well-established opponent-process theory) are not based on a Class A measure for distances between colors. The experiments require participants to compare a sensory stimulus (color) to a mental model: the experiment can not be expressed solely in terms of sensations. Brindley termed “Class B” all measures which can not be expressed solely in terms of sensations\(^1\).

Class B measures can be quite useful, as in the above example, but because Class B measures must pass through observers’ mental models they are less direct and more error-prone. Class B measures risk errors of interpretation and estimation. Further, it is known that a great deal of filtering occurs as sensory data moves to more abstract levels of the nervous system. Consequently, Class A measures, which do not require access to mental models, may be more sensitive than Class B measures. Class A measures may be able to detect trends which would only become apparent with stronger stimuli using Class B measures. These issues are discussed more fully below in reference to presence questionnaires (see Section 2.3.3).

The terms “objective” and “subjective” are widely used in place of “Class A” and “Class B”. This notation is poor, however, as “objective” and “subjective” have too many meanings. For instance, administering a questionnaire asking for presence ratings is a Class B measure, in that it requires a participant to evaluate a mental state. But one could argue that the results are “objective”, from the point-of-view of the experimenter. If the experimenter did not influence the outcome of the experiment, and does not impose a bias on the analysis of the data, is not the outcome “objective”?

Distinct from the Class A/Class B classification are the physiological measures, such as heart-rate or postural changes induced by sensory stimulus. See Section 2.3.4.

Also distinct from the Class A/Class B classification are threshold and multi-

\(^1\) Another way to view the Class A/Class B distinction is that in the case of Class A measures the participant makes a response which is directly congruent to the input, whereas with Class B measures a mental transformation is required.
modal nulling measures. Whereas Class A measures require an observer to compare two sensations, threshold and multi-modal nulling measures do not. For threshold measures, one evaluates an observer’s ability to barely detect some stimulus under different conditions. For multi-modal nulling, one evaluates the degree to which particular stimuli can perceptually overwhelm conflicting stimuli from a different sensory channel. See Section 2.3.5. A specific case of multi-modal nulling is visual-inertial nulling, as used in the presence measure research of Chapter 4.

2.3.2 Class A Presence Measures

It is sometimes suggested that presence should be measured in terms of the degree to which a real scene is indistinguishable from a virtual scene, or in terms of the amount of noise needed to make a real scene indistinguishable from a virtual scene [62, 97, 91, 94]. These might be called “realism” measures. Such measures are “Class A”: they require only a comparison of sensory input, between the real and virtual environments. However, I do not believe that they are satisfactory. The reason is that realism does not appear to be the key factor determining presence. For instance, movies based on animation are no less engaging (or profitable) than those based on realistic imagery. Pausch et al., in summarizing Disney Imagineering’s experience with a virtual environment based on the movie “Aladdin”, mention the importance of content (not simply realism) to the sense of presence [75]. Consistent with this, Welch et al. [108] have recently published results in which pictorial realism was less important to reported presence than either interactivity or short delays.

2.3.3 Class B Presence Measures

The most common means to measure presence is by asking observers to report their sense of presence on a numeric scale, or to adjust a device (such as a lever) to indicate their sense of presence. This technique is known as “magnitude estimation”.
It is an example of a “Class B” measure, since it requires the participant to evaluate a mental state to respond. Magnitude estimation has the advantage of simplicity: this is why it is so widely used (including for the research reported in this dissertation). Unfortunately, magnitude estimation also has fundamental flaws.

Numeric verbal magnitude estimation of presence is likely to produce results of marginal validity. Following its introduction by Stevens [98], magnitude estimation procedures were widely used and produced many useful observations. However, numerous limitations soon became apparent [76, 25]. One of these is the “range effect” [100]: participants’ numerical ratings are strongly influenced by the range of physical stimuli to which they are exposed. The possible influence of range effects can be controlled or evaluated for cases where the physical stimulus dimension is well described; e.g., when relating physical sound intensity to perceived loudness. Similar control or evaluation is not available when the domain for which verbal magnitude estimations are being provided is not described. Presence is a product of the observer’s cognitive processes; physical manipulations to appropriately manipulate perceived presence are only vaguely known. Consequently, we are unable to evaluate possible range effects when performing magnitude estimation of presence. (Similar limitations are encountered when using magnitude estimation of assessment of cognitively-mediated percepts such as pain and motion sickness.)

A second difficulty with magnitude estimation is anchor effects [103], in which the value observers assign to a given condition may depend on the conditions to which it is compared.

The existence of range and anchor effects in magnitude estimation has serious consequences. These effects sharply limit our ability to draw valid conclusions from comparisons between data gathered in separate experiments with different conditions.
2.3.4 Physiological Presence Measures

Physiological measures for presence are in principle very attractive, as at least some of them can be recorded fairly unobtrusively while the subject is participating in the virtual environment. This would potentially allow for a real-time response to the subject’s level of presence. A list of possible physiological measures for presence is given by Barfield and Weghorst [8] and includes posture, muscle tension and cardiovascular and ocular responses to virtual events. Neurological measures might also be considered.

Held and Durlach [38] suggest a measure for presence based on the ability of an environment to produce a “startle response” to unexpected stimuli. More generally, to what extent can a virtual environment produce responses which imply that observers interpret it as the real environment?

Unfortunately, there is currently little evidence that physiological measures correlate well with presence. Sheridan [93] (p. 209) mentions physiological measures, stating that “It is natural to seek an objective measure or criterion that can be used to say that telepresence or virtual presence have been achieved. However telepresence (or virtual presence) is a subjective sensation, much like mental workload, and it is a mental model — it is not so amenable to objective physiological definition and measurement.”

Nevertheless, the use of postural measures have received attention. Ohmi [69] claims a good correlation between the angle of body tilt and the subjective impression of acceleration. Hoshino et al. [43] used body sway to measure the presence of observers exposed to various frequencies of a rolling stimulus displayed on an HMD; on a consumer 3D television; and on a large 3D display. Body sway was measured in terms of head displacements. They reported highest body sway in the case of the HMD with a .33 Hz stimulus2.

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2 In general, one needs to be careful when comparing an HMD to a non-HMD with a body-sway
2.3.5 Threshold and Multi-Modal Nulling Measures

The measures described in this section seek to evaluate spatial perception as directly as possible. They are similar in spirit to Brindley’s “Class A” measures, but need not involve a sensory comparison. Rather, the effect of a stimulus is gauged in terms of its ability to alter perception in some way.

Many such measures take advantage of the close connection between visual and inertial perception. Perception of self-orientation and self-motion is served by a multisensory system that receives inputs from inertial receptors, including the vestibular apparatus and somatic receptors, as well as from the eyes [28, 77, 73, 72]. Changes in inertial receptor response are usually interpreted as altered self-motion or self-orientation. Appropriate manipulation of stimuli to inertial receptors may result in self-motion perception, such as those produced by pitching the head forward while rotating about an earth-vertical axis (i.e., “cross coupling” – see Howard [44]) or by skin pressure cues from a “g seat” [65]. Similarly, visual field flow is usually associated with self-motion. To the extent that the visual surround is interpreted as indicating what is stationary, visual flow with respect to an inertially stationary observer may elicit perceived self-motion. The phenomenon of visually-induced perceived self-motion (vection) has been examined in numerous experiments and is the basis for many motion simulators (see Rolfe and Staples [88]).

Multisensory integration of visual and inertial stimuli occurs in the vestibular nuclei. For example, Waespe and Henn [105] demonstrated that vestibular nucleus neurons may be excited by clockwise inertial rotation. Similar excitation from the same neuron may be evoked by counter-clockwise rotation of the visual surround measure. The HMD may, simply by altering the effective mass of the head, affect body sway (particularly head sway). This would need to be controlled for, for instance by comparing body sway with eyes closed with and without the HMD. It is not clear from the available abstract whether the researchers did so.
(an optokinetic drum). These multisensory neurons, which may underlie self-motion perception, apparently do not distinguish between inertial and visual motion stimuli. Further, because these neurons are in the brain stem, self-motion perception associated with their response may provide a much more robust measure of spatial perception than self-report.

The multisensory nature of the self-motion perception system suggests procedures in which the visual salience of a virtual environment is measured in terms of its ability to overwhelm conflicting inertial perception cues.

*Vection Measures*

Vection refers to the perception of self-motion induced by visual stimuli. An example of this sensation is that if one is seated in a train parked at the station while the train next to it pulls out from the station, one may have a sustained sensation that one is moving in the opposite direction. A possible close relationship between presence and vection will be introduced in Section 3.3.3. In view of this relationship, prior work on vection measures is of special interest. This section borrows from [84].

The simplest types of vection are circular and linear. To induce circular vection, participants may be seated in a chair surrounded by a cylinder (often painted with stripes) which rotates around the participant. Linear vection is typically induced by a display in which objects seem to be approaching or receding.

There is a good discussion of vection measures in Carpenter-Smith *et al.* [17]. Most previous vection studies have been based on a magnitude estimation measure, in which a participant is requested to assign numbers or joystick positions to perceptions. The deficiencies of magnitude estimation were discussed above.

There is a small but interesting literature concerning other measures for vection. This literature can be thought of as dividing into threshold [111, 12] and nulling [112, 48, 49, 50] studies. In threshold studies, one investigates how visual stimuli affect the minimally detectable magnitude of inertial motion (or conversely, how inertial motion
affects the onset of vection). Young et al. [111] examined the interaction of visual and inertial rotation cues, by placing participants on a rotatable chair surrounded by a stripe pattern rotating at constant angular velocity. Among their findings were higher thresholds for the detection of inertial acceleration when the inertial cues conflict with the vection cues. Berthoz et al. [12] placed participants in a cart which moved linearly and induced vection by providing moving images in the lateral field. Their report includes vection onset thresholds in the range of the threshold for visual motion detection, indicating the importance of vision to the perception of motion. A disadvantage of threshold studies is possible variance due to participants adopting different confidence criteria for reporting threshold.

In nulling studies, one set of stimuli are opposed by another and participants are asked to determine the point at which the two stimuli counterbalance each other. Zacharias and Young [112] set up a circular vection nulling experiment. Participants were asked to maintain a stationary position by adjusting their inertial rotation, in the presence of a rotating visual surround and inertial disturbance. Other research using visual-inertial nulling is described by Huang and Young: for yaw rotation [48]; lateral motion [49]; and roll and pitch [50]. These papers developed models for visual-inertial interaction.

Related but distinct is the research by Carpenter-Smith et al. [17]. Prone subjects were translated along their head $x$-axis (fore-aft). In the presence of various inertial and visual surround conditions, participants were asked to report their direction of motion. By running many trials for each participant in each condition, a point of subjective equality (PSE), at which participants would think themselves as at rest, could be determined mathematically for each condition. Shifts in PSE as a result of changes in the visual surround were used to develop, for the first time, a scale for linear vection. (This is not to say that a scale for vection cannot be developed using the more traditional techniques, only that it had not been previously done.)

The presence measurement experiments described in Chapter 4 are an extension
and refinement of the procedure reported by Carpenter-Smith and his colleagues. An attempt is also made to relate visually-induced self motion, indicated by the visual-inertial nulling procedure, to self-reported presence.

*Threshold and Nulling Presence Measures*

Many measures for the “visual effectiveness” of a virtual environment are possible in which the ability of the visual cues to influence spatial perception is evaluated. One can, for instance, measure the extent to which the perception of the gravitational vertical is influenced by conflicting visual vertical cues. For an explanation of why I consider these to be presence measures, see the discussion of the “presence hypothesis” in Section 3.3.3.

Two examples involving the perception of gravity are outlined below.

Hatada *et al.* [36] examined the ability of a display to induce a change in the perceived vertical as a function of horizontal FOV and scene content. They report very small tilts for FOV’s less than 20–30°, and a saturation at about a 5° disturbance to the perceived vertical when the display FOV reaches 80–90°.

Nemire *et al.* [68] reported an experiment to measure “simulation fidelity” in terms of the ability of a VE to induce a change in perception of gravity-referenced eye level (GREL). A pitched optical array can bias a subject’s estimate of eye-level. The authors report that a physical array biases GREL more than an identical virtual array. However, the addition of longitudinal (into the distance) lines to the virtual array removed the performance difference.

The research described in Chapter 4 deliberatelyfactored gravity out by restricting motion cues to the horizontal plane. The reason is that gravity is a very strong cue: it is difficult for visual cues to overwhelm it, particularly when the visual cues are provided by a poor virtual environment. A more sensitive measure is possible when the influence of gravity is controlled for.
### 2.4 Area II: Presence Manipulations

It was mentioned at the top of this chapter that the three areas which it reviews will be related in Chapter 3 to the measurement, manipulation and malformation of selected rest frames. This section surveys the literature relevant to the manipulation of the selected rest frame through foreground occlusions.

There are two aspects to this discussion. The first is the effect of foreground occlusions on presence. The second is whether the effect of foreground occlusions on the selected rest frame can be measured through a spatial performance task (specifically, a roll-correction task associated with inside-out displays).

This section summarizes the literature relevant to the research reported in Chapter 5. It borrows in part from [83].

#### 2.4.1 Foreground Occlusions

A “foreground occlusion” can be thought of as a “peephole” through which to view a display, possibly a peephole for each eye\(^3\) (see Figure 2.1). More formally, a “foreground occlusion” is defined here to be “an obstruction mounted in front of a display in such a way that only the display (and not its boundary) is visible through the obstruction, and such that the display is at a greater visual distance than all other available visual cues.”

Because a foreground occlusion places the display at a greater distance than other visual cues, it encourages the observer to interpret the display as the visual background. The importance of this is discussed below.

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\(^3\) The term “foreground occlusion”, seems preferable to “peephole”, because the latter has strong monocular connotations.
Foreground Occlusion

Figure 2.1: Foreground Occlusion

The foreground occlusion blocks the view of the boundary of the display. In general, foreground occlusions can be binocular.
2.4.2 The Foreground Occlusion Effect

This dissertation develops a somewhat new theoretical framework for discussing foreground occlusions, and emphasizes their application to presence and HMD design. However, the existence of a psychological effect associated with foreground occlusions is not a new observation. The below introduces the literature on foreground occlusions from the fields of vection and the monoscopic viewing of 2D, static pictures.

For those wishing to experience the foreground occlusion effect, a simple technique is to hold up a cardboard box with a hole in it which just blocks the edges of a VCR monitor. For best results, play on the monitor a scene with considerable movement\(^4\). Compare one’s impressions looking through the hole with one eye to an unobstructed view of the monitor at the same distance, again with only one eye.

Foreground Occlusions and Vection

Traditionally, it was believed that a necessary condition for vection was the stimulation of peripheral vision through a wide FOV display. Andersen and Braunstein [5] showed that “central vection” (vection as a result of stimulating only the central visual field with angles as small as 7.5\(^\circ\)) was possible. A similar non-dependence of vection on peripheral vision was reported by Howard and Heckmann [47]. Other research [14, 71, 70] has suggested that a critical issue in determining vection is the apparent relative motion between the self and the perceived visual background.

Because vection is influenced by the visual background, and because foreground occlusions make a display appear to be the visual background, one would expect that a foreground occlusion would increase vection. Howard and Heckmann [47] make essentially this point. “The configuration in which we obtained good centre-consistent vection, namely a moving scene seen at some distance through a window in a large stationary surround, is typical of situations in which the world is seen through the

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\(^4\) I recommend the faster parts of the videotape Over Washington, possibly played on fast-forward.
window of a moving vehicle. The fact that good vection may be obtained under these circumstances is a point to be borne in mind by those who wish to avoid the high cost of producing wide-field displays to induce convincing sensations of self-motion in aircraft simulators.”

Similarly, Mergner and Becker [67] reported that when participants were exposed to a 30° by 30° vection stimulus in central vision, the participants never reported vection when the limited FOV was created by masking (blanking) part of the screen (by putting a box with a small opening over the projection system). In contrast, when the same FOV restriction was created by a mask worn on spectacles, the participants did report vection. In the latter case, the participants felt the vection to be qualitatively less cogent than with full-field stimuli; however, their quantitative estimates were only slightly reduced.

*Monocular Foreground Occlusions and Static Pictures*

The above suggested that the effect of foreground occlusions on vection may be due to the ability of foreground occlusions to alter the perceived visual background. It appears that another factor, depth perception, may also be involved in the effect of monocular foreground occlusions on the perception of static, two-dimensional (2D) pictures. The literature on monocular foreground occlusions for viewing static, 2D pictures is reviewed by Rogers [87].

It has long been observed that the appearance of three dimensions in a picture is more striking under certain viewing conditions, such as viewing the picture with one eye only and by using a peephole or a lens in a reduction screen or viewbox. A number of old viewing devices make use of one method or another to produce their sometimes powerful effects. The usual explanation is that the restricted view enhances the effectiveness of pictorial-depth information by reducing the conflicting flatness informa-
tion that specifies a picture’s objective surface...

Peephole viewing is monocular and head motion is prevented, and this should enhance perceived depth as described above. A peephole or a lens also restricts the observer’s view of the picture itself, hiding the frame and surrounding surfaces. Loss of the visible frame and discontinuous surrounding surfaces reduce information for the picture as a flat object (perhaps even for the presence of a surface at all), potentially enhancing the illusion of depth in the picture. This is the oft-cited reason for the success of the various picture-viewing devices.

The following is a personal observation, in keeping with Rogers’ discussion of the effect of monocular foreground occlusions on depth perception in 2D pictures. When viewing Claude Monet’s *Boats at Argenteuil* through a monocular foreground occlusion, the components of the image appear larger than when viewed monocularly from the same position without the foreground occlusion. A possible explanation is that sizes are difficult to judge monocularly; that surrounding cues, for instance from the picture frame, would ordinarily affect monocular size perception; and that with these cues removed, the perceived size of the picture components increases. The overall scaling-up of the image components may stretch the perceived depth.

Two possible mechanisms for the effect of foreground occlusions have been presented in the last two sections. For vection, literature involving binocular foreground occlusions suggested that their effect may be due to an alteration of the perceived visual background. For monocular foreground occlusions applied to 2D, static images, the alteration of perceived depth was also mentioned. One might ask: “is the alteration of perceived depth a significant factor in the effect of binocular foreground occlusions?”

I suggest that depth perception is not a significant factor for binocular foreground occlusions. The reason is that strong stereoscopic depth cues are present both with
and without the binocular foreground occlusion. Consistent with this, I do not re-
member any of the participants run in the experiments described in Chapter 5 sponta-
neously mentioning that depth perception was affected by a binocular foreground occlusion. Nor did I have that impression myself.

2.4.3 Inside-Out Displays

Inside-out displays occasionally produce an interesting failure of spatial inter-
pretation known as “control reversals”. For reasons given in Chapter 3, it was thought that foreground occlusions might reduce this problem, resulting in a performance measure for the foreground occlusion effect. The literature on inside-out displays is summarized below.

The two simplest ways to represent the roll of an aircraft on a cockpit display are either: to keep a representation of the ground stationary and roll an aircraft icon; or to keep the aircraft icon stationary and roll the ground representation (see Figure 2.2). The former is referred to as an outside-in display; the latter, as an inside-out display. The terminology arises as follows. If one views a plane from above and behind (“outside”), a roll is seen as the plane moving with respect to the ground. Hence, a display in which the aircraft icon moves is called “outside-in”. Conversely, if one sees the roll of the plane from inside looking out, what one sees with respect to the plane is the ground moving up either the left or right window of the cockpit. Hence, a display in which the ground representation moves is called “inside-out”\(^5\).

Despite the congruence between inside-out displays and the view out the window of the cockpit, inside-out displays are prone to a misinterpretation known as a “control reversal”. When a control reversal occurs, the pilot inadvertently attempts to

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\(^5\) There is a refinement called a “frequency-separated” display which combines the “outside-in” and “inside-out” approaches. There are data pointing to the superiority of frequency-separated displays; see, for instance, [10]. However, frequency-separated displays are beyond the scope of the current discussion.
A Inside-out; and B outside-in depictions of a plane rolled down towards the right.

Figure 2.2: Inside-Out and Outside-In Roll Representations
control the representation of the ground, rather than of the plane. For instance, in Figure 2.2 (A) we see a representation of a plane rolled with its right wing down. To correct for the roll, the pilot should bank the plane to the left. However, in a “control reversal” pilots will instead act as if they should correct for the roll by “pushing down” on the ground representation (i.e., banking the plane to the right).

Of course, pilots are well-trained to interpret inside-out displays correctly, and control reversals are rare. Nevertheless, Roscoe mentions that “it is possible – even for airline pilots – to confuse the moving horizon bar of the gyroscopic attitude indicator and the fixed airplane symbol when they find themselves suddenly and unexpectedly in an unusual flight attitude.” [89] Roscoe suggests that this condition may be implicated in “graveyard spirals”, which cause approximately 100 deaths per year in the U.S. in general aviation, as well as occasional commercial disasters, perhaps including the 1994 USAir 737 crash.

Given that the inside-out display is congruent to the view out the window of the cockpit, and that control reversals do not occur when looking out the window, why do control reversals occur when using inside-out displays?

There is a good discussion of this issue by Roscoe et al. [90] (p. 70):

The problem of pilot errors on moving-horizon attitude displays may be explained in the context of the psychological phenomenon of figure and ground. Although figure-ground definitions emphasize static aspects of the visual field, dynamic aspects dominate the flight situation. Psychologically, the part of the field of view that appears to be stationary is customarily called the background, and the object that is moving is called the figure. When the entire visual field moves in relation to the observer’s eye, as occurs with head movement, the observer usually perceives correctly that the background is stationary.

The question then becomes: do the figure and ground relationships
between the aircraft and the outside world change when the pilot shifts attention from the outside world to the attitude indicator on the panel inside the cockpit? If the pilot’s frame of reference changes when a small, abstract instrument representation of the outside world is all that is available, as opposed to the outside world itself, this change must involve a shift in the figure-ground relationship. Specifically, the aircraft’s instrument panel or even the framed aperture of an individual display face becomes the background against which the display elements move.

Roscoe et al. [90] (p. 70) mention an interesting technique for removing control reversals, which was the subject of Pilot Study AIIP2.

The highly resolved, dynamic, literal image in full color presented on a display screen by a projection-type flight periscope consistently yields the same stable figure-ground relationships for all pilots regardless of display size. With display screens subtending visual angles ranging from 30 degrees down to 7.5 degrees (a 2-inch screen viewed from 15 inches) and presenting a forward looking view as narrow as 3.75 degrees (x2 magnification), no control reversal was observed during more than 135 hours of flight experimentation involving more than 25 different pilots of widely varying experience.

Another method for reducing the control reversal problem is the “Malcolm horizon” [64], in which a light representing the horizon is extended across the cockpit. Aside from being easier to attend to than a small horizon display, this approach makes “use of the neural programming which naturally orients us with the horizon.” The authors discuss the importance of stimulating peripheral vision in order to achieve intuitive orientation with the horizon.
2.5 Area III: Motion Sickness

This section is concerned with simulator sickness, an unfortunate side-effect of virtual interfaces mentioned in Chapter 1. The literature summarized here is relevant to the research reported in Chapter 6. This section borrows in part from [80].

Simulator sickness refers to the experience of malaise arising from exposure to computer-generated or computer-mediated environments. It is a major issue impeding the introduction of advanced interfaces for both non-inclusive simulators as well as inclusive virtual environments. Simulator sickness imposes limitations on the use of these interfaces for training and entertainment applications as well as raising liability concerns. An extensive survey of the literature on simulator sickness is available in [57]. Also available are abstracts from a recent conference on motion sickness [3].

One can think of simulator sickness as having two components. The first arises from imperfections in the technology, such as lag or geometric distortions. This component might be termed “interface sickness” (see Appendix F for a discussion of this terminology). Interface sickness is a serious problem, but one which is likely to become less so as technology advances. For an extended discussion, including a technique for measuring the effect of display imperfections on the vestibulo-ocular reflex, see [22].

The second component of simulator sickness arises from the accurate presentation of stimuli which are inherently nauseogenic. This component is called “motion sickness”. Thus, a part of simulator sickness is believed to be closely related to other types of motion sickness such as sea sickness, car sickness, and space sickness. The relationship between various forms of motion sickness is discussed in [54].

Motion sickness refers to a pattern of symptoms including nausea, headaches

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6 For instance, the presentation of visual motion cues in the absence of inertial self-motion cues from the chair in which the observer is seated.
and disorientation⁷. According to the standard sensory rearrangement theory, “all situations which provoke motion sickness are characterized by a condition of sensory rearrangement in which the motion signals transmitted by the eyes, the vestibular system and the non-vestibular proprioceptors are at variance either with one another or with what is expected from previous experience” [29, 85, 86].

Crampton has restated the sensory rearrangement theory in a manner which closely parallels an application of the rest frame construct to be introduced in Section 3.3.5. According to Crampton [19] (p. 30):

Animals have an orientation constancy such that brain mechanisms support a perception of up and down, right and left, of the stable environment in which they maneuver. This perception is a complex one that includes the distinction between the animal moving its eyes or body and the movement of objects in its space. The perception is supported by neural mechanism or memory that is continually updated or tested by vestibular, visual, auditory, chemical, kinesthetic, and somatosensory inputs that are often associated with motor activity such as visual search, limb movement, and locomotion. This orientation constancy may be extended to include geographical features important to migration and navigation.

In the course of a species’ history, orientation constancy is assembled through selection over generations and then modified by each individual’s experience until almost all combinations of inputs are interpreted such that the animal can effectively perform within its space environment to

⁷ It is puzzling that vomiting would be a response to motion sickness. An evolutionary hypothesis put forward by Treisman [102] suggests that food poisoning produces abnormal perceptions, which are therefore linked with vomiting. Motion sickness mimics the abnormal perceptions due to food poisoning, and therefore triggers the vomiting response.
sustain, defend and reproduce its own kind. If a new sensory input is so discordant with the orientation constancy (a mismatch) that the performance of the animal is degraded, certain species display symptoms of lethargy, anorexia, salivation, and then vomit. In addition, man shows facial pallor and reports nausea.

In accordance with sensory rearrangement theory, motion sickness is likely to be an ever-increasing problem as virtual interfaces become more compelling. More compelling stimuli from the virtual interface cause the nervous system to give the stimuli more weight, increasing the sickness caused by any sensory conflicts.

Finally, while this dissertation is the first full-scale presentation of the rest frame construct and its implications, its parts have been aired previously and have begun to work their way into the literature. A group led by Deborah Harm at NASA has applied the ideas from Chapter 3 to develop the first successful predictor for space sickness based on perceptual style [34, 33]. Astronauts were divided into two groups: those whose selected rest frame in weightlessness was determined more by the visual scene (VS), and those whose selected rest frame was determined more by their own body axis (IZ). “It was found that orientation reference type had a significant effect, resulting in an estimated 3-fold increase in the expected motion sickness score on flight day 1 for VS astronauts. Estimated probabilities of no symptoms ranged from 0.46 (Flight Day 1) to 0.79 (Flight Day 7) for IZ astronauts, and from 0.31 (Flight Day 1) to 0.62 (Flight Day 7) for VS astronauts.”
Chapter 3

INTRODUCTION TO THE RESEARCH

To say that the world is resting on the wheel of space or on the wheel of wind is not the truth of the self or the truth of others. Such a statement is based on a small view. People speak this way because they think that it must be impossible to exist without having a place on which to rest.

— Dogen, 13th Century [21]

3.1 Introduction

The purpose of this chapter is to introduce the rest frame construct (RFC); to classify its applications; and to briefly summarize and index the experiments described in subsequent chapters. The dissertation is organized logically rather than chronologically. The intent is to explain concisely rather than in actual sequence the work conducted as part of this research. To streamline the presentation substantial effort is left undescribed, due to a lack of definitive results or because subsequent experiments were more clear.

3.2 The Rest Frame Construct

The RFC is a way of summarizing much of the literature on spatial perception. While the idea it captures is not fundamentally new, formulating it in a particular way is convenient for currently purposes. The RFC fairly naturally suggests lines of research involving visual-inertial nulling presence measures; techniques for manipulating presence; and techniques for reducing simulator side-effects.
The RFC derives from the observation that humans have a strong perception that certain things are stationary. For instance, we ordinarily perceive the Earth as stationary. We typically interpret relative motions between the Earth’s surface and objects on or near it (such as bicycles or aircraft) as implying that the object in question is moving, while the Earth remains stationary ("at rest").

From a mathematical point-of-view, our strong perception that certain things are stationary is quite strange. Given a relative motion between two entities, it makes as much sense to interpret either (or neither) as stationary. Our nervous system could, in principle, choose to agree with Copernicus that the Sun is stationary and provide us with a complex impression of our motion on the Earth with respect to the Sun. Or, in principle, if one moves one’s hand back and forth in a room, one could perceive the hand as stationary and the room as moving in the opposite manner. Both of these possibilities are completely legitimate, mathematically, but are also completely foreign to our perception.

The suggestion made here is that the nervous system selects certain things as being stationary in order to minimize its calculations. For instance, if one is primarily concerned with navigating on the Earth, it is useful to assume the Earth’s surface to be stationary and to use it as the basis for spatial comparisons. Similarly, it is much more efficient to compute the motion of one’s hand with respect to a room which is assumed to be stationary than the converse. (For similar reasons, mathematicians and physicists are often concerned to choose a specific coordinate system which simplifies a particular problem.)

The RFC simply formalizes this discussion. Borrowing from physics, a coordinate system used to define positions, angular orientations and motions is called a “reference frame”. The particular reference frame which a given observer takes to be stationary is called the “rest frame” for that observer.

1 As an example of a reference frame which is not a rest frame, consider a train which is perceived as moving through a landscape. One might notice where some person is on the train. Since one
The "rest frame construct" states that:

The nervous system has access to many rest frames. Under normal conditions, one of these is selected by the nervous system as the comparator for spatial judgments. We call this the "selected rest frame." In some cases, the nervous system is not able to select a single rest frame.

3.3 Implications of the Rest Frame Construct

The RFC has a number of direct implications. These are listed in the below subsections.

3.3.1 The Importance of the Visual Background

If the selected rest frame is picked in such a way as to minimize calculations, we would expect it to be heavily influenced by what is perceived to be the visual background. The reason is that the visual background generally defines the largest set of coherent spatial cues in the environment. Consequently, calculations performed by the nervous system may be simplified by assigning this set of cues to be the rest frame, and thus as forming the comparator for spatial judgments.

One should note, however, that the primary issue is simplifying calculations, not an inherent need to make use of the visual background. For cases in which one's task involves the visual foreground one would expect this foreground to determine the selected rest frame. One example of this is that while the night stars are clearly in the visual background, one usually perceives a change in the position of the stars, not the Earth. The reason, presumably, is that the task of concern to the nervous system is navigating with respect to the surface of the Earth, not with respect to the stars. Hence, it is much more practical to take a rest frame aligned with the surface of the

is making a judgment with respect to the train, which is perceived as moving, the train acts as a moving reference frame.
Earth. The relative motion between the Earth and the stars is therefore interpreted as a motion of the stars\textsuperscript{2}. Similarly, when checking the instrument panel of an aircraft, one will tend to perceive the panel as being at rest (defining the selected rest frame). It is only when one again looks out the window and switches to a task of navigating visually with respect to the Earth’s surface that one again perceives the aircraft (and the panel) as moving.

The “induced motion” of the visual background reported in Pilot Study AHIP2 (Appendix D, involving a driving simulator) is also of interest in this regard. In this case, a conflict between the motion of the visual background and of the visual foreground was perceived as a motion of the background, even though it was the background which was in agreement with the inertial cues. The driving-simulator task under study required the participant to navigate with respect to the visual foreground. Apparently, this was sufficient to result in the foreground being selected as the rest frame, even in the presence of conflicting rest frame cues from the background and from inertial cues.

3.3.2 Six Types of Spatial “Illusions”

The selected rest frame is hypothesized to underlie our perception of position, angular orientation and motion, both for self and for external objects. Crossing “self” or “external object” with “position”, “orientation” or “motion”, we would expect that visual background manipulations which alter the selected rest frame should produce 6 types of “illusions”\textsuperscript{3}.

\textsuperscript{2} Mike Weissman, a HTIL staff member, gives an extreme example of this. He reports that when on a boat in the Pacific Ocean, after a couple of days when looking up at the night sky the swaying of the boat was perceived as a swaying of the stars.

\textsuperscript{3} These six conditions are termed “illusions” here because they are often so labelled, and for lack of a better term in general circulation. If one accepts the physics viewpoint that absolute motion, position and angular orientation are meaningless, then it is incorrect to think of these six
For 5 of these 6 cases (the sixth being “self and position”) it is well-known that visual background manipulations can produce the indicated illusion. The six possibilities are itemized below.

**Self and Motion.** The visually-induced perception of self-motion is called “vection”. For instance, if one is seated in a stationary car at a traffic light, and the adjacent car rolls backwards, one may have a sustained impression that one is moving forwards. Recent work implies that vection is heavily influenced by one’s relative motion with respect to the perceived visual background. See Section 2.4.1.

**External Objects and Motion.** If one moves the background behind an object, one often has the impression that the object is moving in the opposite direction to the background. This is called “induced motion” [106].

**Self and Orientation.** If one is placed in a room in which the walls are tilted, one tends to perceive that one is tilted in the opposite direction [45].

**External Objects and Orientation.** A tilted background can alter one’s perception of the orientation of an object in the foreground with respect to gravity [45].

**Self and Position.** It is suggested that presence, the sense of “being somewhere”, encompasses this kind of illusion. See the discussion of the “presence hypothesis”, below.

**External Objects and Position.** Visual background manipulations may alter the perceived distance to objects, which is a form of position illusion. For instance, in the “corridor illusion”, linear perspective is used to alter the perceived depth (and therefore size) of an object [60].

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conditions as reflecting illusions. They are simply different perceptions. (Although a case could be made for the “corridor illusion” being a true illusion, since relative distances are physically meaningful, at least for small velocities.) I would prefer to describe these six conditions with the terms “rest frame phenomena” or “rest frame shifts”. 
3.3.3 The Presence Hypothesis and Presence Measures

Given the suggested importance of selected rest frames to perception, an interesting question is whether we have any corresponding subjective constructs. That is, to what degree are we aware of the selected rest frame we are using? One possibility is that the sense of presence is related to the choice of rest frame. If one thinks of presence as the sense of “being somewhere”, and the sense of “being somewhere” as referring to one’s sense of position, angular orientation and motion, then the possible link between presence and the selected rest frame becomes clear. This way of thinking brings to mind the following “presence hypothesis”, which states that:

The sense of presence in an environment reflects the degree to which that environment influences the selected rest frame.

Thus, in this formulation, the sense of presence encompasses the six spatial illusions discussed above.

One advantage of the presence hypothesis is that it links the sense of presence squarely to something which appears to be quite fundamental to spatial perception. A second advantage is that it makes possible a wide range of presence measures. If the presence hypothesis is true, then the degree of presence in a virtual environment can be measured through perceptual experiments in which the rest frame implied by the virtual environment conflicts with the rest frame implied by the external environment. The ease with which the virtual rest frame overwhelms the external rest frame perceptually can then be used as a presence measure. Such a measure might provide a more robust method than questionnaires for determining the best combinations of FOV, resolution, update rate, etc. to engender presence.

The presence hypothesis also suggests why presence may be related to such issues as the enjoyability of an interface, or the degree of meaning extracted from it. To the extent that a virtual interface is able to engage the attention, it will define the task
at hand and thus influence the selected rest frame\textsuperscript{4}. The capture of the selected rest frame is in turn evidenced by the sense of presence.

It must be emphasized, however, that the presence hypothesis is an hypothesis: the posited link between presence (as a phenomenon observers are aware of and as measured by self-reports) and measures based on rest frame conflict needs to be tested experimentally. Experiments along these lines are reported in this dissertation.

The objection is sometimes made that the “presence hypothesis” is too simple to capture all of what we mean by presence. This argument takes two forms. The first form is that presence in a virtual environment is known to depend on a multitude of factors, including, for instance: the observer’s state of mind going into the virtual environment; the weight of the HMD (if there is one); the power of the computer supporting the virtual environment; the sensory modalities used; and the content of the virtual environment. How could something which depends sensitively on so many things have a simple definition?

A response is that it is quite common for many factors to influence something, while that “something” is itself very simple. For instance, the speed of an automobile depends on a wide range of variables, such as the mood of the driver; aerodynamics; and the quality of the engine, tires and road. But the speed itself is entirely trivial, and can be measured with a simple speedometer.

The second form of the “too simple” objection is that the presence hypothesis leaves certain things out. The best example is perhaps the sense of presence we feel in a story when reading a novel. Is it claimed that this, too, has to do with selected rest frames?

This depends how one wants to draw the lines. It would not greatly hurt the basic argument, which is concerned with spatial perception, to carve off text-based presence as something separate. I am inclined, however, to suggest that text-based

\textsuperscript{4} In accordance with the argument given above that the selection of rest frame is driven by efficiency considerations linked to the current task.
presence can be thought of in terms of selected rest frames, although the rest frame implied by a novel is abstract and does not lend itself to the kind of visual-inertial nulling measures to be described below.

In the end, the presence hypothesis is not so much true or false as useful or useless. Emphasizing selected rest frames suggests certain kinds of research questions. It is on the depth and outcome of these questions that the presence hypothesis should ultimately be judged.

3.3.4 The Importance of Foreground Occlusions

The importance of the visual background to determining the selected rest frame was discussed above. In accordance with the presence hypothesis, one would expect that the visual background would also play a role in determining the sense of presence.

It is known that increasing the FOV of a display, everything else being equal, increases the sense of presence. This is consistent with the above argument: as the FOV of a display is increased, it absorbs more of the visual field, which should increase the likelihood that the contents of the display will be interpreted as defining the visual background. If the contents of the display are interpreted as defining the visual background, they will influence the selected rest frame; this should in turn increase the sense of presence.

The importance of FOV is well-known to the virtual environments community. Less well-known is the importance of a foreground occlusion (see Section 2.4.1). Because a foreground occlusion places the display at a greater distance than all other visual cues, it becomes more likely that the contents of the display will be interpreted as defining the visual background.

One might consequently predict that a foreground occlusion will influence the selected rest frame and (therefore) increase reported presence. Two sequences of experiments on this question are reported in this dissertation. The first sequence examined the effect of foreground occlusions on reported presence.
The second sequence, adapted from the problem of control reversals in inside-out displays (see Section 2.4.3), sought a performance measure related to the influence of a foreground occlusion on the selected rest frame. Roscoe et al.’s “figure and ground” discussion of the control reversal problem has a natural expression in terms of the RFC. In order for an inside-out display to be interpreted correctly, a difference in the orientation of the ground representation and the aircraft icon has to be interpreted as a roll of the aircraft icon, not of the ground representation. That is, the ground representation has to define the selected rest frame. This happens automatically when looking out the window of the real aircraft: the real ground defines the visual background, and hence the selected rest frame, and hence a change in the roll angle between the real ground and the real aircraft is interpreted as a roll of the real aircraft.

The interpretation of a roll depicted on an inside-out display is much less intuitive than a roll seen out of a real cockpit window. The ground representation on the inside-out display does not have a wide FOV and does not define the visual background. The selected rest frame tends to be determined by the cockpit as a whole. Since the aircraft icon on the inside-out display is fixed with respect to the cockpit, a change in the roll angle between the ground representation of the inside-out display and the aircraft icon is interpreted as a roll of the ground representation. In the absence of training or under stressful conditions, this can lead to control reversals.

In view of this line of thinking, it is interesting to consider the two remedies for control reversals discussed in Section 2.4.3. The use of a “highly resolved, dynamic, literal image in full color presented on a display screen” is consistent with factors known to increase the sense of presence (see Section 2.2). The presence hypothesis suggests the following: the “literal image” increases the sense of presence, which equivalently maps the selected rest frame into the natural reference frame for the display (the ground representation), which consequently reduces control reversals.

\footnote{However, an alternative explanation is possible, which is that the more detailed cues simply make the ground representation easier to interpret, for low-level visual perception reasons. The more}
The second remedy discussed was the Malcolm horizon, which extends the ground representation of the inside-out display across the cockpit. In part, the value of the Malcolm horizon arises from providing a wide FOV stimulus which makes it easier to detect small angular motions. However, recent research on narrow FOV vection (see Section 2.4.1) shows that motion perception depends heavily on what one perceives to be the visual background. It therefore seems plausible that the Malcolm horizon also has a more indirect influence: expanding the FOV increases the chance that the ground representation will be interpreted as the visual background, and hence that the ground representation will influence the selected rest frame.

More generally, one might expect that any manipulation which increases the sense that the ground representation of the inside-out display is in the visual background would serve to reduce control reversals. One such manipulation is to provide a foreground occlusion. In view of the Malcolm horizon, and in view of the above discussion of the parallel between increasing the FOV and providing a foreground occlusion, one might predict that placing a foreground occlusion in front of an inside-out display would serve to reduce control reversals.

This idea is hardly of practical value for real cockpits, since a foreground occlusion which blocked out other visual cues at the same or greater distance as the inside-out display (i.e., the rest of the cockpit) would not be useful. Whether a foreground occlusion can in principle reduce control reversals is an interesting question, however, for at least two reasons.

1. It provides a possible performance measure for the foreground occlusion effect.

2. It is a test of the theory that the perceived visual background is a determining factor in the occurrence of control reversals. This might be of relevance to the design of virtual cockpits presented on a display, in which the ground represen-

detailed cues may make it easier to detect the angle between the plane and the ground.
tation could be put at a greater distance than the rest of the virtual cockpit using stereoscopic, accommodative, or other depth cues.

Just as the frequency of control reversals is a potential measure for the foreground occlusion effect, it is also a potential measure for any other presence manipulation. This suggests that the effect of a wide variety of display manipulations on presence could be measured by evaluating the frequency of control reversals.

3.3.5 A Technique for Reducing Simulator Side-Effects

This section borrows in part from [80].

Given the hypothesized importance of rest frames to spatial perception, we would expect that a difficulty in selecting a consistent rest frame would have serious consequences. The rest frame construct suggests that motion sickness does not arise from conflicting motion signals per se\(^6\), but rather from conflicting rest frames deduced from those motion signals. That is, what is crucial is not the full set of motion cues in an environment, but rather how those motion cues are interpreted to influence one’s sense of what is and is not stationary. For instance, if one is seated on a bench watching a flock of birds approaching, one has conflicting motion signals (the birds indicate a relative motion, the inertial cues do not). However, one is very unlikely to become motion sick because one’s perceptual system is unlikely to interpret the flock of birds as defining the stationary rest frame, and, as such, indicating self-motion. Other visual rest frame cues, from the ground or the sky, are more influential than the flock of birds.

From this point-of-view, the key to avoiding motion sickness is not to remove all conflicting motion cues, but rather to remove those discrepancies which indicate conflicting rest frames. It was argued above that the selected rest frame is heavily influenced by the perceived visual background. Therefore, a foreground/background

\(^6\) As suggested by the standard sensory rearrangement theory. See Section 2.5.
division of the visual field could be introduced as a means to test the application of
the rest frame construct to motion sickness.

A moving visual background (for instance, a wide FOV simulator display) combined with an absence of inertial motion cues is likely to increase motion sickness symptoms. The rest frame indicated by the visual background indicates self-motion, whereas the inertial rest frame cues do not.

This suggests that providing a visual background in agreement with inertial cues may serve to reduce simulator sickness, even when the foreground cues are not in agreement with inertial cues. The application to simulator design is that providing an “independent visual background” (IVB) which appears behind the simulator’s usual visual “content-of-interest” (CI) may provide a simple technique for reducing simulator sickness. The IVB can be made consistent with the inertial rest frame even if the CI (foreground) is not. Two experiments to test this prediction are reported in this dissertation\textsuperscript{7}.

### 3.4 Division of the Research

The rest frame construct and presence hypothesis together suggest three closely related areas of research. These have to do with the measurement, manipulation and malformation of selected rest frames.

**Area I.** *Presence reflects selected rest frame decisions.* This suggests that it is possible to measure presence by creating a conflict between real and virtual rest frame cues and then evaluating the relative influence of the virtual cues on the selected rest frame. Thus, a scale for presence can be constructed in terms of the ability of a virtual environment to perceptually overwhelm conflicting real stimuli.

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\textsuperscript{7}It should be emphasized that the IVB technique can only reduce the component of simulator sickness which is due to rest frame conflict (i.e., motion sickness). It cannot reduce interface sickness. See Section 2.5 and Appendix F for a discussion of this distinction.
Area II. What stimuli influence selected rest frame decisions? This leads to the study of techniques for manipulating the selected rest frame and the sense of presence in virtual environments. In particular, the use of foreground occlusions was investigated.

Area III. What are the consequences when the appropriate selected rest frame is unclear? This produces at least two interesting subcases. Area III A. Visual cues determine the selected rest frame, despite conflicting inertial cues. As discussed in Section 3.3.2, this suggests a useful way of linking together presence and six classes of visual illusions. Area III B. No functional selected rest frame is formed at all. As a slight refinement to sensory rearrangement theory, it was suggested in Section 3.3.5 that this condition is the underlying cause of motion sickness.

A typical dissertation takes as its topic a single, often narrow, line of research and pursues it to a definitive conclusion. The present dissertation research was not conducted in that fashion, as a matter of deliberate policy. The reason is that the usefulness of the RFC lies precisely in its ability to show relationships, and to allow borrowings, between distinct areas of research. The test of a unifying formulation does not lie in one specific line of research, but rather in its ability to consistently provide useful guidance across its domain of applicability. Hence, as described below, this dissertation reports on separate lines of research in each of Areas I, II and III, as well as an experiment on the influence of cognitive factors on presence and preliminary work on the application of foreground occlusions to reducing “luning” (an unfortunate side-effect of certain binocular displays).

3.5 Guide to the Experiments

Table 3.1 provides a taxonomy of the experiments reported in this dissertation and where their descriptions can be found. All but two of these studies (CogE1 and BRP1) addressed questions in Areas I, II, or III. The experiments are labelled with
a short index, according to the following scheme. The index begins with the area of research ("AI", "AII" and "AIII", for Areas I, II and III; "Cog" for cognitive factors on presence; and "BR" for binocular rivalry. The next letter is either "P" for pilot studies (intended only for guidance, rather than to achieve definitive results) or "E" (for experiments which are intended to be fairly definitive, at least for the particular conditions under study). Descriptions of the experiments are usually found in the main chapters; the pilot studies are reported in abbreviated form in the appendices. The final part of the experiment index is a number, giving the logical order of the experiment within its area of research.

**Importance of Presence.** Described under this topic is an experiment showing that presence is affected by the meaningfulness of the stimuli, with all other variables held constant. Conversely, presence may be a partial measure for the meaningfulness of the stimuli. This strengthens the assertion of this dissertation that presence is worthy of serious study.

**Area I: Presence Measures.** Described under this topic is a technique for measuring presence based on multi-modal nulling.

**Area II: Presence Manipulations.** Described under this topic are experiments on the manipulation of the sense of presence, as applied to HMD's and inside-out displays.

**Area III: Motion Sickness.** Described under this topic is a technique for reducing simulator side-effects using an independent visual display. (However, AIIIIP2 found an interesting induced motion effect of the independent visual background which may be useful as a presence measure.)

**Binocular Rivalry.** Described under this topic is a literature review and pilot study on the application of foreground occlusions to reducing a binocular rivalry problem know as "luning". Luning is a significant problem for some HMD's which partially overlap the scene presented to the two eyes.
### Table 3.1: Dissertation Experiments

<table>
<thead>
<tr>
<th>Label</th>
<th>Title</th>
<th>Location</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Importance of Presence</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CogE1</td>
<td>Cognitive Influences on Presence</td>
<td>Appendix A</td>
</tr>
<tr>
<td><strong>Area I: Presence Measures</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>AIP1</td>
<td>Wide Field-of-View</td>
<td>Appendix B</td>
</tr>
<tr>
<td>AIP2</td>
<td>Orientation</td>
<td>Appendix B</td>
</tr>
<tr>
<td>AIE1</td>
<td>Narrow Field-of-View (Reported Presence)</td>
<td>Chapter 4</td>
</tr>
<tr>
<td>AIP3</td>
<td>Narrow Field-of-View (Nulling Measure I)</td>
<td>Appendix B</td>
</tr>
<tr>
<td>AIP4</td>
<td>Narrow Field-of-View (Nulling Measure II)</td>
<td>Appendix B</td>
</tr>
<tr>
<td>AIE2</td>
<td>Meaningful/Random</td>
<td>Chapter 4</td>
</tr>
<tr>
<td><strong>Area II: Presence Manipulations</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>AIIP1</td>
<td>Foreground Occlusions and Field-of-View</td>
<td>Appendix C</td>
</tr>
<tr>
<td>AIE1</td>
<td>Foreground Occlusions and Reported Presence I</td>
<td>Chapter 5</td>
</tr>
<tr>
<td>AIE2</td>
<td>Foreground Occlusions and Reported Presence II</td>
<td>Chapter 5</td>
</tr>
<tr>
<td>AIIP2</td>
<td>Inside-Out Displays and Optical Flow</td>
<td>Appendix C</td>
</tr>
<tr>
<td>AIIP3</td>
<td>Inside-Out Displays and Foreground Occlusions I</td>
<td>Appendix C</td>
</tr>
<tr>
<td>AIE3</td>
<td>Inside-Out Displays and Foreground Occlusions II</td>
<td>Appendix C</td>
</tr>
<tr>
<td><strong>Area III: Motion Sickness</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>AIIIE1</td>
<td>Independent Visual Background I (low-end)</td>
<td>Chapter 6</td>
</tr>
<tr>
<td>AIIPP1</td>
<td>Undisturbed Postural Stability</td>
<td>Appendix D</td>
</tr>
<tr>
<td>AIIIE2</td>
<td>Independent Visual Background II (low-end)</td>
<td>Chapter 6</td>
</tr>
<tr>
<td>AIIPP2</td>
<td>Independent Visual Background III (high-end)</td>
<td>Appendix D</td>
</tr>
<tr>
<td><strong>Binocular Rivalry</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>BRP1</td>
<td>Foreground Occlusions and Binocular Rivalry</td>
<td>Appendix E</td>
</tr>
</tbody>
</table>
3.6 Experimental Configurations

This section gives logical diagrams and brief descriptions of the experimental configurations used in this dissertation.

3.6.1 Area I: Presence Measures

The experiments of Chapter 4 measured the relative effect of different visual conditions on the perception of self-motion. A visual-inertial nulling technique was used in which the strength of the visual stimuli was measured by its ability to overwhelm conflicting inertial motion cues. The technique is outlined in Figure 3.1.

3.6.2 Area II: Presence Manipulations

The experiments of Chapter 5 measured the effect of a foreground occlusion on reported presence and on control reversals in an inside-out display. A foreground occlusion is defined in this dissertation as “an obstruction mounted in front of a display in such a way that only the display (and not its boundary) is visible through the obstruction, and such that the display is at a greater visual distance than all other available visual cues.” This is diagramed in Figure 2.1 on page 15.

The experiments of Chapter 5 compared conditions with and without a foreground occlusion, keeping the FOV constant across conditions.

3.6.3 Area III: Motion Sickness

The experiments of Chapter 6 measured the ability of a stationary visual background to reduce simulator side-effects resulting from a moving visual foreground.

The conditions are outlined in Figure 3.2.
Figure 3.1: Presence Measure Experimental Configuration

A. Participant is seated in a chair which oscillates in yaw \(i.e.,\) in the horizontal plane while wearing an HMD. The HMD shows a scene which also oscillates in yaw. B. In the real world, when one turns to the right the visual field flows to the left. The sense of self-motion is towards the right. C. The visual motion in the HMD can be set to turn in the same direction as the inertial motion. In this case, the inertial cues make one think one is moving to the right, whereas the visual cues make one think one is moving to the left. The sense of self-motion depends on their relative strength. D. Any visual-inertial phase angle is possible.
In both conditions, a scene rotating at 60°/sec around the vertical axis was shown in an HMD. The scene was recorded on videotape by rotating a camera on a tripod in the counter-clockwise direction as viewed from above in a plaza on the University of Washington campus. The IVB condition A provides a real background visible through the half-silvered mirror of the HMD which is consistent with the lack of inertial self-motion cues. The IVB was rated by participants as being less visible than the HMD scene. The non-IVB condition B placed an occlusion behind the half-silvered mirror such that only the rotating scene was visible.
3.7 Equipment

Many of the experiments described in subsequent chapters used the same equipment. This section summarizes their features.

3.7.1 Computer Software and Hardware Platforms

The presence measure experiment of Chapter 4 made use of a standard PC and "Virtual TV" (VTV) software from Warp, Ltd. [1] which allows a very large image to be stored in memory. The VTV software "precomput[es] the rendering of a scene from all possible view orientations. This permits unlimited pan/tilt/roll/zoom freedom at high framerates on standard VGA cards." [107] Instead of dynamically computing updates to the visual scene, oscillations were implemented more efficiently by indexing into different portions of the image. This allowed for a frame-rate of 60 Hz. Unfortunately, it also meant that the scene could not be displayed in stereo: the same indexed image was sent to both eyes of the HMD. To keep the frame-rate consistently at 60 Hz in all conditions, an "approximate dewarp" mode was used, which does not precisely simulate oscillations around a fixed center-point. For the same reason, a rather low resolution of 240x320 pixels was used.

The reported presence/foreground occlusion research reported in Chapter 5 made use of the Division ProVision 100. The ProVision 100 is a hardware/software platform designed specifically for supporting virtual environments. It combines an Intel 486 platform with dedicated stereo graphics, three-dimensional audio\(^8\), and low-latency virtual world interactivity in a single chassis. It can be accessed by standard UNIX applications. It comes with dVS, Division's software environment, which provides a distributed foundation for applications and a high level object-oriented programming interface. It is used in conjunction with the Division dVisor HMD described below.

The environment used for the research described in Chapter 5 was "SharkWorld".

\(^8\) The audio capability was not used for the experiments reported in this dissertation.
"SharkWorld" was developed by Division, Ltd. and features a texture-mapped underwater scene with a sunken ship and various moving sea creatures. The participants tried to catch sharks using a virtual net which followed real hand position.

The research involving control reversals (see Appendix C) made use of images generated by a Silicon Graphics Reality Engine II and displayed on a Silicon Graphics 20" monitor.

3.7.2 Driving Simulator

As described in Appendix D, a 1-day pilot study was conducted using the Hughes Research Laboratories driving simulator. For a full description of the simulator, see [101]. The simulator features the front half of a car mounted before an LCD front projection screen with an FOV of 160° horizontal by 35° vertical.

3.7.3 Head-Mounted Displays

Three HMD's were used during the course of the dissertation experiments. The below specification are taken from [96]. Specifications sometimes vary slightly depending on the source.

For the reported presence experiments described in Chapter 5, the Division dVisor was used. The dVisor features 294x141 pixels, horizontal FOV 105°, vertical FOV 41°, and 46° stereo overlap. It weighs 8.8 pounds.

The presence measure experiments described in Chapter 4 used the Virtual Research VR4 HMD. The VR4 has the advantages over the dVisor of higher resolution; of being much less heavy and bulky; and of being light-tight. Unfortunately, the VR4 has a lower FOV than the dVisor. The VR4 features 247x230 pixels, horizontal FOV 48°, vertical FOV 36°, and 100% stereo overlap. It weighs 33 ounces.

The experiments reported in Chapter 6 made use of the Virtual i-O i-glasses! VTV/VPC. This HMD features 263x230 color pixels and a 30° horizontal by 24°
vertical FOV with 100% overlap between the two eyes. It weighs 8 ounces. The image is displayed on a semi-transparent half-silvered mirror. The half-silvered mirror has the crucial advantage (for the experiments reported in Chapter 6) of allowing both a see-through and occluded mode. In the see-through mode, the image on the half-silvered mirror is overlaid on the external environment. By mounting an occlusion behind the mirror, the HMD can also be used in a mode in which only the display itself is visible.

3.7.4 Rotating Chair

The experiments in Section 4 and the pilot studies in Appendix B involved oscillating participants in yaw (i.e., around the vertical axis) while providing an HMD scene which oscillated with the same period but conflicting phase. This research made use of a chair mounted on a Contraves Goerz Co. Direct Drive Rate Table Series 800 controlled by a Neurokinetics, Inc. Motion Simulator Controller (see Figure 3.3). Participants were seated with their spine aligned with the gravitational vertical. The chair moved in yaw (i.e., around the vertical axis).

The chair is fitted with a 5-point harness. Since the experiments described in this dissertation were conducted at low amplitudes, only the lap belt was used.

3.7.5 Balance Platform

For Experiment AIIIIE2, reported in Chapter 6, a device was used to measure postural stability before and after exposure to a condition. This device was a Chattecx Balance System platform which permits the determination of the participant’s center-of-gravity based on signals from force plates under each foot. Calculations were based on the dispersion of the participant’s center-of-gravity in centimeters in the two horizontal dimensions over a 10 second period sampled at 100 Hz. Lower dispersion values indicate greater stability.
Figure 3.3: Rotating Chair

Rotating chair used in the visual-inertial nulling experiments. It allows for oscillations in the horizontal plane under program control. This equipment was graciously loaned to Dr. Parker by the National Aeronautics and Space Administration.
3.7.6 Foreground Occlusions

Chapter 5 and Appendix C describes two sequences of experiments: the first involving reported presence measures and the second a screen-based spatial orientation measure. For the first sequence, a very small foreground occlusion was needed which could fit easily under an HMD. In the second, it was possible to mount a larger device on a tabletop in front of the monitor. Consequently, two completely different foreground occlusions were used for the two sequences of experiments, as discussed below. In both cases, the foreground occlusion was clearly perceived as being in front of the monitor.

Reported Presence Foreground Occlusion Experiments

The sequence of experiments described in Section 5.2 made use of a pair of Lucas Products Corporation white “Super Sunnies” goggles, of the kind commonly used in tanning booths. These are worn directly over the eyes, and therefore fit easily under an HMD. The 1.27 cm diameter central ultra-violet protector in front of each eye was removed: this had the effect of providing clear vision in an FOV limited to a central circle. As the goggles rest close to the eyes, translation of the pupil during eye rotation results in a difference between “direct FOV” (the range one can foveate on by turning the eyes but not the head) and “peripheral FOV” (the total range one can see using peripheral vision while looking straight ahead without turning the head)*. We measured direct FOV for the foreground occlusion at 40°, peripheral at 60°.

To avoid infection, in all experiments the goggles were washed with rubbing alcohol between participants.

To compare the foreground occlusion condition (i.e., the condition in which the

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9 The terms “direct” and “peripheral” FOV were invented for the purposes of this experiment. I do not know of established terms for these ideas.
participants wore the tanning goggles) to the same FOV without the foreground occlusion, black construction paper was placed over the HMD screens with holes corresponding to what was visible through the tanning goggles.

**Inside-Out Display Foreground Occlusion Experiments**

The sequence of experiments described in Section C.2 explored the effect of a foreground occlusion on an inside-out display roll-correction task. For these experiments, the foreground occlusion was a black, monocular iris mounted on a desk in front of a 20" monitor. The iris could be adjusted to narrow or widen the FOV. The iris was mounted in such a way that its height could be easily altered to provide each participant with a comfortable seated view of the monitor through the foreground occlusion. An adjustable padded chinrest was also provided. The iris and chinrest were surrounded by black tarp which blocked out any peripheral visual cues from the laboratory. After choosing which eye to use for the trials, participants were fitted with an eyepatch which blocked the other eye. This avoided binocular rivalry distractions without the need for squinting. Room lights were turned off so that illumination came almost entirely from the monitor.

The monitor displayed a circular scene surrounded by a black annulus which covered the remainder of the screen. In the foreground occlusion condition, participants were asked to narrow the iris so that they could just barely see a red circle just inside the annulus. Thus, the iris blocked out all visual cues closer than the scene. To provide matched trials without the foreground occlusion, participants expanded the iris to match a red circle such that the black annulus surrounding the scene was clearly visible. In both conditions, the red circle disappeared prior to the start of the trials.

The monitor was viewed from a distance of about 20 cm. The FOV of the scene was about 30°. The red circle for the foreground occlusion condition was set at about 27°. In the wider condition, the FOV was about 45°.
3.8 General Methods and Measures

Many of the experiments described in subsequent chapters used similar techniques. This section summarizes their common features. Specializations are presented as needed for the individual experiments.

Every experiment was conducted with the prior approval of the University of Washington’s Human Subjects Review Committee, and prior informed consent was obtained from all participants. Except where stated, data taken from the experimenters were not used, and all participants were unpaid volunteers not familiar with the experimental hypotheses.

3.8.1 Presence Questionnaire

For a discussion of presence questionnaires in general, see Section 2.3.3.

With minor variations for scene differences, the following questionnaire was used in the foreground occlusion reported presence experiments described in Chapter 5 and in Appendix C; and in the visual-inertial nulling experiments of Chapter 4 and in Appendix B. Reported presence was measured by taking the average of the responses to the below questions.

1. In shark world, I felt like ... (1 = I was standing in the laboratory, wearing a virtual reality helmet.) (7 = I was in some sort of ocean, near a shark-infested shipwreck.)

2. How real did the virtual world seem to you? (1 = about as real as an imagined world.) (7 = indistinguishable from the real world.)

3. To what extent were there times when you felt that the virtual world became the "reality" for you, and you almost forgot about the real world outside? (1 = at no time.) (7 = almost all the time.)
4. Did the virtual world seem more like something you saw or someplace you visited? (1 = something I saw.) (7 = some place I visited.)

5. Did the virtual world seem more like a picture or more like a scene looked at through a window? (1 = like a picture.) (7 = like looking through a window.)

As the above questions produced similar patterns of responses, and since a shorter questionnaire was desired which could be conveniently used during exposure, rather than as a post-test, the experiments described in Chapter 4 relied on a version of the first question. This question appears to most readily capture the informal description of presence as the sense of “being someplace”. (See the “presence hypothesis”, Section 3.3.3.)

3.8.2 Embedded Figures Test

The experiment reported in Chapter 4 made use of an embedded figures test (EFT) provided by Consulting Psychologists [2]. This is a standardized measure of cognitive style and analytical ability. The test requires finding simple forms which are embedded in larger figures. The score is the average time in seconds to detect the simple forms. Thus, higher scores reflect greater difficulty in analyzing a part separately from a wider pattern. (Or, viewed more positively, a greater tendency to perceive complete patterns rather than their separate components.)

The EFT is closely associated with other perceptual measures which require the participant to analyze part of an organized field independently of the whole [110]. These include tests of perception of orientation to the vertical (the rod-and-frame test and the body adjustment test); of certain illusions and reversible perspective; of similar auditory and tactile disembedding tasks; and of problem-solving which requires “disembedding” a part from its current environment.

The link between the EFT and “field dependence” is particularly interesting, for current purposes. Field dependence measures the degree to which an observer has
difficulty analyzing part of an organized field independently of the field. For instance, the “rod-and-frame” test requires one to sit in a totally darkened room and adjust to the gravitational vertical a tilted luminous rod centered within a tilted luminous frame, while the frame remains in its initial position of tilt. “Reflecting in each case the strong influence of the immediately surrounding field upon the way in which one of its parts is perceived, the person who takes very long to discover the simple figure in the complex EFT design is also likely to tilt the rod far toward the tilted frame and his own body far toward the tilted room.” [110]

The visual-inertial conflict set up by the research of Chapter 4 required participants to extract inertial motion cues from conflicting visual motion cues. This bears a resemblance to the rod-and-frame test. A question addressed in Chapter 4 is therefore whether between-subject differences in the ease of visual-inertial disambiguation is related to EFT scores.

More generally, presence reflects the degree to which one is “pulled into” a (usually) visual environment, despite external cues. By analogy with the rod-and-frame experiment, one might expect between-subject differences in any valid presence measure to have at least some correlation with EFT scores.

3.8.3 Simulator Sickness Questionnaire

The simulator sickness questionnaire (SSQ) [55] is an extensively researched protocol for measuring reported simulator sickness. It breaks simulator sickness into three components: nausea (nausea, stomach awareness, increased salivation, burping); oculomotor (eyestrain, difficulty focusing, blurred vision, headache) and disorientation (dizziness, vertigo). The components can be combined to give a total SSQ score. The SSQ was used as a measure in the simulator sickness experiments of Chapter 6.

See Appendix G for the full specification of the SSQ.
3.8.4 The PEST Convergence Procedure

The experiments described in Chapter 4 and in Appendix B used successive approximations to find the inertial amplitude at which participants crossed over between inertial and visual dominance (i.e., between having their perception of self-motion determined by inertial and visual cues). The inertial amplitude adjustments after each trial were made following the Parameter Estimation by Sequential Testing (PEST) procedure [99], which is a simple convergence algorithm developed for psychophysics experiments.

The PEST procedure obeys the following four rules:

1. On every reversal of step direction, halve the step size.

2. The second step in a given direction, if called for, is the same size as the first.

3. The fourth and subsequent steps in a given direction are each double their predecessor (except that... large steps may be disturbing to a human observer and an upper limit on permissible step size may be needed).

4. Whether a third successive step in a given direction is the same as or double the second depends on the sequence of steps leading to the most recent reversal. If the step immediately preceding that reversal resulted from a doubling, then the third step is not doubled, while if the step leading to the most recent reversal was not the result of a doubling, then this third step is double the second.

The PEST procedure ends when the step size drops to a pre-determined amount. The estimate is the level called for by the last step\(^{10}\).

\(^{10}\) Actually, in Chapter 4 I chose to report the range between the last amplitude tested and the next determined by the PEST procedure.
In practice, the fact that each trial in the visual-inertial nulling experiments required a few minutes forced a fairly rapid convergence, which in turn required a final step size sufficient to allow for a rapid convergence (this was taken to be an amplitude of $5^\circ$/sec in the experiment reported in Chapter 4, or $3^\circ$/sec if the two conditions run in parallel would otherwise be tied). Hence, the subtleties of rules 3 and 4, above, rarely came into play.
Chapter 4

AREA I: PRESENCE MEASURES

Door meten tot weten. (To knowledge by measurement.)

— Kammerlingh, Dutch low temperature physicist

4.1 Introduction

This chapter addresses the “presence hypothesis” from Section 3.3.3 and its application to the measurement of presence. The “presence hypothesis” claims that the degree to which the rest frame implied by a virtual environment perceptually overwhelms a conflicting rest frame implied by the real (external) environment should constitute a presence measure\(^1\).

The following questions are addressed in this chapter.

1. How should a rest frame conflict measure be implemented?

2. Is the presence hypothesis correct? That is, does a measure based on real-virtual rest frame conflict evaluate our subjective sense of presence?

3. What is the test-retest correlation of a rest frame conflict measure?\(^2\)

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1 See Section 2.3 for an introduction to psychological measures in general, as well as their previous application to presence and vection. See Section 3.7 for a description of the equipment.

2 Test-retest correlation evaluates the self-consistency of a measure. A high test-retest correlation is crucial to a good measure, because a measure can be no more accurate than it is consistent.
4. How is the rest frame conflict measure related to field dependency? Presence and field dependency both measure the degree to which one is drawn into a visual scene. It might therefore be expected of a good presence measure that between-subject variation would correlate with between-subject variation in field dependency$^3$.

In principle, many real-virtual rest frame conflict measures are possible. See Section 3.3.2 for a classification of spatial “illusions” which can be induced by visual stimuli. Any of these can be harnessed to create a rest frame conflict measure, by implying a rest frame with the virtual cues which conflicts with the rest frame implied by the real cues. The rest frame conflict measure then records the degree to which the observer’s spatial perception is dominated by the virtual, rather than real, cues.

A straight-forward rest frame conflict measure can be based on altering the perception of the vertical. Visual cues from a display may be set to indicate the vertical to be different from gravity. Measuring the perception of the vertical, for instance by having the observer adjust a rod to indicate the perceived vertical$^4$, measures the degree to which the visual rest frame has overwhelmed the inertial rest frame.

While rest frame conflict measures based on perceived orientation are quite possible, they face the difficulty that the inertial perception of gravity is very strong. This tends to make the influence of the visual scene difficult to measure, particularly for virtual environments which are not very compelling. The research reported in this chapter therefore focused on a measure in which gravity is not a factor: conflicting inertial and visual self-motion cues in the horizontal plane. Given conflicting inertial and visual self-motion cues, one’s perception of self-motion may be determined by

$^3$ See Section 3.8.2 for a further discussion of these issues.

$^4$ See [45] for a discussion of the perception of the vertical, Section 2.3.2 for prior research on presence measures of this type, and Section 3.8.2 for a description of the rod-and-frame test and its relationship to other psychological measures.
the inertial cues, by the visual cues, or by some combination. As the inertial amplitude is lowered, it becomes increasingly likely that the visual cues will determine the perception of self-motion.

The approach was to develop a “visual-inertial nulling measure” for finding the inertial amplitude at which participants cross-over between inertial and visual dominance of the perception of self-motion. The hypothesis was that a visual condition which was more “presence inducing” would require stronger inertial cues to match the visual cues perceptually, and that this would be reflected in a higher visual-inertial cross-over amplitude.

The technique developed here is intended primarily as a proof-of-principle: to establish a rest frame conflict measure which factors out gravity, and to examine its relationship to a reported presence measure and the test-retest correlation of both measures. The measure used in this chapter is not a final answer to the need for sensitive and convenient presence measures. In particular, it is cumbersome (it requires the full attention of the participant to perform the measurement task) and is not suited to interactive virtual environments (since the time-course of both the visual and inertial motion cues have to be tightly controlled by the experimenter). Pilot Study AIIP2 (see Appendix D) raised the possibility of a more graceful rest frame conflict measure, based on the induced motion of a background grid. See Chapter 8 for a discussion of this possibility.

Two experiments are described in this chapter. The first experiment, AIE1, examined three FOV’s: 16°, 32° and 48° FOV. It was predicted that wider FOV would result in higher presence on both a self-report and visual-inertial nulling measure. The second experiment, AIE2, focused on a meaningful/random visual scene manipulation. The random condition was created by randomizing the pixels in the meaningful scene. The meaningful/random manipulation appeared more likely to result in a clear

\footnote{48° was the widest FOV available for the Virtual Research VR4 HMD used in these studies.}
main effect on both measures than the FOV manipulation described above. The main effect was predicted to indicate higher presence on both measures in the meaningful condition.

The meaningful/random manipulation reported here is similar to the meaningful/meaningless manipulation described in Appendix A. The meaningful/meaningless manipulation compared meaningful with matched meaningless chess positions. This found a difference in reported presence on a purely cognitive variable, in favor of higher presence for the meaningful condition.

The meaningful/random manipulation described in Experiment AIE2 is not a purely cognitive manipulation. In addition to affecting level of meaning, it also affects low-level perceptual factors such as number and distribution of edges. Thus, while the results of Experiment AIE2 could be taken as supporting the conclusion of Appendix A that meaning affects presence, it does not do so unambiguously.

4.2 General Methods

See Section 3.7 for a description of the equipment.

In all research described in this chapter, participants were seated upright in a chair which oscillated sinusoidally in yaw (i.e., in the horizontal plane). A fan was mounted on the back of the chair to mask any vibratory or auditory noise it might produce. Participants wore a Virtual Research VR4 HMD which displayed a (non-stereographic) scene which also oscillated sinusoidally in yaw. The HMD blocked off all visual cues from the laboratory. The image motion was controlled by Warp Ltd.’s “Virtual TV” software, as described in Section 3.7. Both inertial (chair) and visual (HMD) oscillations were always at .1 Hz. However, the phase angle between the inertial and visual motion was varied.

The primary image used was taken from Maui, and consisted of tropical vegetation overlooking water. In separate experiments, this image was manipulated either by
varying the FOV or by randomizing the location of each pixel in the image.

Reported simulator sickness data was gathered before and after every session, using the pre- and post-exposure SSQ. These data were used only as an informal diagnostic to examine whether the experiment was causing malaise and needed to be re-designed. Sickness did not appear to a problem, as long as exposures in each trial were kept to one or two minutes and separated by a brief break while conditions were altered. During the break, participants were requested to close their eyes and relax, and the chair was brought smoothly to rest.

4.2.1 Overview of the Visual-Inertial Nulling Measure

This section introduces the rest frame conflict measure studied below. A scale for the visual effect of a stimulus is defined in terms of its ability to influence the inertial perception of motion. This "visual-inertial nulling" technique draws its strength from the close connection between the visual and inertial motion perception systems in humans. Because these two systems are so closely related, it may be possible to measure subtle changes in the input to one system in terms of a change in perception arising from the other. See Section 2.3 for further details.

Description of Visual-Inertial Phase Angles

The research described below manipulates the phase angle between the visual and inertial motions in order to produce conflicting self-motion cues. A confusing point about visual-inertial phase angles is that, ordinarily, visual and inertial motion cues are 180° out of phase (see Figure 3.1, on page 42). For instance, when one turns to the right, the visual field flows to the left. More explicitly, if one stares perpendicular to one’s shoulders while turning to the right, after having turned, a point which one was initially observing will have moved to one’s left.

Thus, the "ordinary" situation is for inertial and visual stimuli to be 180° out
of phase. The “most contradictory” condition occurs when the inertial and visual stimuli are exactly in phase. For instance, if the visual background moves to one’s right, one tends to feel that one is moving to the left. If the inertial motion is also to the right, then one has completely conflicting motion cues.

It is confusing to use the term “in phase” to describe inertial and visual stimuli which are completely conflicting in terms of their effect on self-motion perception. To avoid this problem, the phase angles in this chapter are given between the vection and inertial curves rather than between the visual and inertial curves. That is, a phase angle of zero implies a consistent sense of self-motion from the two kinds of stimuli. The vection curve differs from the visual curve by 180°. A phase angle of +90° is defined here to imply that one’s inertial sense of self-motion is 90° ahead of one’s visual sense of self-motion. Conversely, a phase angle of −90° implies that one’s inertial sense of self-motion is 90° behind one’s visual sense of self-motion.

The word “consistent” is used to indicate a vection-inertial phase angle of zero, and “conflicting” to indicate all other vection-inertial phase angles.

Visual and Vestibular Motion Detection

The visual-inertial nulling measure involves the interaction between visual and inertial motion cues. An important inertial motion detector for humans is the vestibular system in the inner ear\(^6\). This section summarizes the relationship between visual and vestibular motion perception as it affects the visual-inertial nulling measure.

All of the nulling experiments described in this dissertation involved both visual and inertial sinusoidal oscillations in the horizontal plane at .1 Hz. The .1 Hz frequency was picked for two reasons. The first had to do with the dynamics of the semi-circular canals of the vestibular system, which detect angular accelerations of the head. As taken from Howard [46], natural head motions occur in the frequency

\(^6\) Humans have other inertial motion detectors, for instance in the torso [104].
range of .1 Hz to 5 Hz. The semi-circular canals are tuned for these frequencies. In this range, the detection of inertial oscillations should have a gain of close to 1 and very little phase offset. This implies that participants should be able to accurately detect the inertial oscillation in this frequency range (provided that the amplitude is sufficient). At higher frequencies, the canals exhibit phase lag; at lower frequencies, phase lead. To test the ability of visual cues to overwhelm inertial cues, we needed participants to be receiving accurate inertial information. This required that the experiment be conducted somewhere in the .1 Hz to 5 Hz range.

A second consideration was to pick a range in which both the visual and vestibular systems are used for motion detection. Otherwise, an effective conflict between the two could not be created. The visual system dominates at very low frequencies; the vestibular system, at high frequencies. The gain for the visual and inertial systems are equal at about .02 Hz [112]. This was a reason for picking the lowest value in the .1 Hz to 5 Hz range; it is closer to .02 Hz.

Aside from frequency considerations, the measurement of inertial amplitude is also an important issue. In principle, inertial amplitude can be measured in many ways, for instance: angular displacement; peak angular velocity; peak angular acceleration, etc. The best choice appears to be the maximum peak-to-peak difference in velocity across a complete cycle. This is because while the semicircular canals respond to accelerations in their individual planes of rotation, they integrate these accelerations to report velocities [46]. Benson et al. [9] mention that “The frequency coded signals from the ampullary receptors [of the semicircular canals] are much more closely related to the angular velocity of the head than to its angular acceleration.” They add that “many experiments (reviewed by Guedry [31]) in which thresholds for the detection of whole-body rotation were determined have shown that threshold is primarily dependent upon the change of angular velocity (Δθ) achieved by the test stimulus rather than by its acceleration, provided the duration of the stimulus does
not appreciably exceed the integration time constant of the semicircular canals.\textsuperscript{7}

In the same paper, Benson \textit{et al.} \cite{benson1998} give the mean threshold for the detection of whole body yaw rotations in 30 subjects as 1.5\(^{\circ}\)/sec. The velocity stimulus followed a single cosine bell trajectory.

\textit{The Determination of Inertial Cross-Over Amplitudes}

The procedure described here determines the relative influence of visual and inertial stimuli on the sense of self-motion. See Figure 3.1, on page 42, for a diagram illustrating the procedure.

Both inertial (chair) and visual (HMD) oscillations were at .1 Hz, but the phases conflicted. The degree to which participants identified with the visual vs. inertial self-motion cues was determined by having them indicate with a toggle switch the perceived right and left extremes of the inertial motion. If the inertial amplitude is sufficiently low, one tends to inadvertently indicate the vection cues, rather than the inertial motion of the chair (even though, with one’s eyes closed, one could correctly follow the chair motion at the same inertial amplitude). The term “inertial dominance” will be used when the observer correctly indicates the inertial motion, and the term “visual dominance” when the observer indicates the vection stimulus, despite attempting to signal the chair motion.

Using the PEST procedure (see Section 3.8.4) to adjust the inertial amplitude after each trial, the inertial amplitude at which the participant switched between visual

\textsuperscript{7}Without going into the details of vestibular physiology, the integration time constant refers to the time period over which a stimulus detected by the semicircular canals continues to be signaled. The integration time constant is partly affected by a recovery time within the semicircular canals (about 4 seconds) and partly, apparently, is due to “the time taken for central neural events to subside” \cite{benson1998}. The combined integration time constant is over 12 seconds. By comparison, the duration of one cycle of an inertial wave at .1 Hz, as used for the experiments described here, is 10 seconds.
and inertial dominance was determined. This is termed the “cross-over amplitude”. The presence hypothesis implies that the cross-over amplitude should be a presence measure. The research described below investigated this measure.

The experiments described in this chapter ran trials of two visual conditions in parallel in each session. To counter-balance order effects, trials from the two conditions followed an ABBA pattern within each session. In addition, the condition with the first trial was counter-balanced across participants, and within participants across sessions.

The visual amplitude for all trials was 30°/sec. This was picked for saliency after informal trials. The experiment began with an inertial amplitude of 15°/sec. The initial step-size for the PEST procedure was 10°/sec. The termination condition was a step-size of at most 5°/sec⁸. This value were picked to converge fairly quickly, in order to keep sessions in the 1 hour range, counting introductions, administering the Embedded Figures Test, simulator sickness questionnaire data collection, etc.

The cross-over data reported below are the midpoints of the range to which the inertial amplitude was narrowed in °/sec. This is half the maximum peak-to-peak velocity difference over one cycle. See above for a discussion of these units.

The phase difference between the inertial and vection cues was always ±90°. A 90° magnitude phase difference is useful in that the two curves are sufficiently far apart that the difference between visual and inertial dominance is readily apparent in the data, but not so far apart that the vection and inertial self-motion cues become clearly distinct. A magnitude of 90° was picked on the basis of informal trials.

In Pilot Study AIP3, a random choice of either ±90° phase angle was used, to avoid a possible learning effect which might occur from holding the phase angle constant. This resulted in a poor test-retest correlation (.38), possibly due to a systematic

⁸ In a few cases, only a resolution of 10°/sec could be achieved due to equipment or scheduling problems.
difference in the difficulty of the two phase angles\textsuperscript{9}.

Pilot Study AIP4 used the same vection-inertial phase angle of $+90^\circ$ for all trials. For a small participant sample ($n = 4$), this resulted in a test-retest correlation of .99. There was not a within-subjects drop in the cross-over amplitude from the first to the second session. All 4 of the participants believed (incorrectly) that the phase angle was changing across trials\textsuperscript{10}. This suggested that a learning effect might not be a major issue with a single phase angle.

Each participant was given an initial practice trial with the HMD turned off at an inertial amplitude of $10^\circ$/sec. This served both to introduce the participant to the procedures and to check their inertial motion detection. Only one participant was screened out on the basis of this test\textsuperscript{11}.

Between trials, while the chair was at rest, participants were asked to relax and close their eyes. Before each new trial, after starting the chair in motion, participants were asked to count down by 7’s with their eyes closed for 25 seconds from an arbitrary number selected by the experimenter. This provided a distraction which prevented the participant from “locking in” to the inertial motion. They then continued to count down for an additional 25 seconds with their eyes open. This gave the vection cues time to build up an effect. Next, participants were asked to stop counting and start signaling the perceived endpoints of the chair’s inertial motion while attending to the visual scene.

In written and oral instructions, participants were asked to

1. Pay attention to the visual scene when your eyes are open.

2. Signal how you think the chair is physically moving.

\textsuperscript{9} It should be remembered that .1 Hz is at the bottom of the ideal angular motion-detection range for the vestibular channels. Below this frequency, phase lead becomes an issue. See above.

\textsuperscript{10} A possible reason for this incorrect perception will be given in Section 4.4.5, below.

\textsuperscript{11} Recall from above that the mean threshold for detection of whole body yaw rotations is $1.5^\circ$/sec.
3. Close your eyes after each trial until asked to open them.

A trial always ran for at least 4 signals. Often the trial was halted after four signals, as all four would indicate either clear visual or clear inertial dominance. If not, approximately 30 seconds to a minute of signals would be recorded to examine whether a clear trend developed. The trial would then be halted and the average phase distance of the signals from the inertial and vection stimuli would be recorded. After the trial, the chair was brought smoothly down to zero velocity.

At inertial amplitudes markedly below or above the cross-over amplitude, participants signaled perceived endpoints of their inertial motion which were roughly a phase distance of $10^\circ$ from either the vection or inertial cues, depending on whether the participant was in inertial or visual dominance. As the cross-over amplitude was approached, the phase distances equalized in a predictable if somewhat haphazard manner. This raised the issue of what decision to make for the PEST procedure if the phase angles between the participant’s signals and the two motion stimuli were indistinguishable (defined to mean: within $10^\circ$ of each other). The decision made was as follows: if the cross-over amplitude had already been determined to within a $5^\circ$/sec range, simply take the current amplitude as the cross-over amplitude. If not, retest.

4.2.2 Overview of the Reported Presence Measure

Reported presence data was gathered in both experiments described in this chapter. The order of conditions was counter-balanced across participants and (in Experiment AIE2) sessions. Each experiment gathered two reported presence ratings per condition, in order to examine test-retest reliability. Both experiments used the same

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12 The accuracy of the inertial motion signaling was limited by human response, rather than equipment considerations. Under ideal conditions, simply watching the chair moving with no distractions, it was not difficult to signal the endpoints of the chair motion to within $5^\circ$, often less.
procedure, except that Experiment AIE1 recorded two presence ratings per condition in a single session, and Experiment AIE2 recorded one presence rating per condition in each of two sessions. In Experiment AIE1, initial presence ratings were obtained for each of three conditions in random order. Immediately afterwards\textsuperscript{13}, presence ratings were obtained for the same three conditions in an independent random order.

Participants were familiarized with the general idea of presence prior to the experiment by the following written description.

Experiencing a virtual world can lead to a conflict in where you focus your attention. For instance, you may feel as if you are in the place suggested by the virtual world. At the same time, you may be aware of the contradictory fact that you are in the laboratory, wearing a head-mounted display. The following question assesses the extent to which you feel “immersed” in the virtual world, and whether the intensity of this feeling is different in the various conditions. There are no “correct” answers. Please make your ratings as honestly as possible. Pick a number between 1 and 7, where “1” means “very little” and “7” means “very much so”.

Participants were also familiarized (prior to the experiment) with the particular presence question to be asked. The question was as follows:

1. I feel like I am in ... (1 = The laboratory, wearing a head-mounted display.) (7 = In the virtual world.)

For a discussion of this presence question, see Section 3.8.1.

When reported presence data was gathered, participants were seated in a chair which oscillated sinusoidally at .1 Hz, with an amplitude of 20°/sec. They wore a

\textsuperscript{13} Within minutes.
Virtual Research VR4 HMD showing the (non-stereoscopic) scene oscillating sinusoidally at .1 Hz, with an amplitude of 30°/sec. The inertial and vection stimuli were consistent \(i.e.,\) what one would expect in the real world. The visual amplitude was chosen for saliency, and the inertial amplitude was chosen to be in the upper range of inertial amplitudes likely to be experienced during the visual-inertial nulling measure trials. The non-equality of the inertial and visual amplitude was deliberate, to be consistent with the normal state of affairs in the visual-inertial nulling measure trials\(^{14}\).

Participants were asked to observe each condition, which were shown for one minute each. Immediately afterwards, participants were exposed to the same conditions, and, after 10 seconds, asked the presence question about each condition.

Before obtaining repeated measures for the same condition, participants were instructed to answer the question in the same way if they felt the same as the first time, and differently if their impressions had changed.

### 4.3 Experiment AIE1: Narrow Field-of-View (Reported Presence)

#### 4.3.1 Introduction

Experiment AIE1 and Pilot Studies AIP3 and AIP4 jointly examined the reported presence and visual-inertial nulling measures for three FOV’s (16°, 32°, and 48°). AIE1 gathered reported presence data for reference against the cross-over data gathered in Pilot Studies AIP3 and AIP4. Half of the 20 participants from Experiment AIE1 proceeded to the more lengthy nulling studies, AIP3 or AIP4\(^{15}\). It was

\(^{14}\)It is interesting that, judging from informal discussions, participants never had a clear perception of what the difference was between the inertial and visual amplitudes, or even whether there was a difference.

\(^{15}\)Running more participants in AIE1 than AIP3 and AIP4 took advantage of the relative briefness of AIE1 to gather more data on reported presence, and served to gain practical experience with
hypothesized that wider FOV’s would result in higher reported presence.

4.3.2 Summary

See Table 4.1.

Table 4.1: Experiment AIE1: Field-of-View (Reported Presence)

<table>
<thead>
<tr>
<th>Background</th>
<th>Investigated the effect of FOV on reported presence.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hypothesis</td>
<td>Reported presence will be higher at wider FOV’s.</td>
</tr>
<tr>
<td>Methods</td>
<td>16°, 32°, and 48° FOV’s were compared. There were 1-minute pre-exposures to each condition, order counter-balanced, with 2 per-exposure presence ratings recorded.</td>
</tr>
<tr>
<td>Results</td>
<td>48° FOV produced significantly higher reported presence than the other two conditions. However, about 1/3 of participants did not rate the widest FOV as invoking the highest presence.</td>
</tr>
<tr>
<td>Conclusions</td>
<td>The predicted main effect was found. The 1/3 of participants who did not follow this pattern may reflect a foreground occlusion effect at narrow FOV.</td>
</tr>
</tbody>
</table>

4.3.3 Methods

There were 20 adult volunteers (16 male, 4 female) all but 1 naive to the experimental hypothesis. Fifteen reported more than 10 minutes prior experience with virtual environments. General data about participants are given in Table 4.2.

For general methods, including the image used and how the per-exposure presence ratings were taken, see Section 4.2. Participants were given a one-minute pre-exposure to each condition, in random order, during which they were asked to examine the scene new equipment.
Table 4.2: Participant Overview for Experiments AIE1

<table>
<thead>
<tr>
<th>Id</th>
<th>Gn</th>
<th>Age</th>
<th>Prev</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>M</td>
<td>41</td>
<td>1</td>
</tr>
<tr>
<td>2</td>
<td>M</td>
<td>29</td>
<td>0</td>
</tr>
<tr>
<td>3</td>
<td>M</td>
<td>43</td>
<td>1</td>
</tr>
<tr>
<td>4</td>
<td>M</td>
<td>42</td>
<td>1</td>
</tr>
<tr>
<td>5</td>
<td>M</td>
<td>26</td>
<td>1</td>
</tr>
<tr>
<td>6</td>
<td>M</td>
<td>36</td>
<td>1</td>
</tr>
<tr>
<td>7</td>
<td>M</td>
<td>29</td>
<td>1</td>
</tr>
<tr>
<td>8</td>
<td>F</td>
<td>40</td>
<td>1</td>
</tr>
<tr>
<td>9</td>
<td>M</td>
<td>27</td>
<td>1</td>
</tr>
<tr>
<td>10</td>
<td>M</td>
<td>34</td>
<td>1</td>
</tr>
<tr>
<td>11</td>
<td>F</td>
<td>43</td>
<td>0</td>
</tr>
<tr>
<td>12</td>
<td>M</td>
<td>25</td>
<td>1</td>
</tr>
<tr>
<td>13</td>
<td>M</td>
<td>36</td>
<td>0</td>
</tr>
<tr>
<td>14</td>
<td>M</td>
<td>21</td>
<td>0</td>
</tr>
<tr>
<td>15</td>
<td>F</td>
<td>27</td>
<td>1</td>
</tr>
<tr>
<td>16</td>
<td>M</td>
<td>27</td>
<td>0</td>
</tr>
<tr>
<td>17</td>
<td>M</td>
<td>27</td>
<td>1</td>
</tr>
<tr>
<td>18</td>
<td>F</td>
<td>38</td>
<td>1</td>
</tr>
<tr>
<td>19</td>
<td>M</td>
<td>53</td>
<td>1</td>
</tr>
<tr>
<td>20</td>
<td>M</td>
<td>48</td>
<td>1</td>
</tr>
</tbody>
</table>

*Id* is the participant number. *Gn* gives the gender, *Age* the age in years, and *Prev* is “1” if the participant had more than 10 minutes of prior experience in virtual environments, “0” otherwise.
and gather their impressions. Subsequently, per-exposure presence ratings were taken for each condition in an independent random order.

Three FOV conditions were compared: 16°, 32°, and 48° (the widest available on the HMD used). FOV was restricted by blacking pixels around the boundary of the display (by the same proportion vertically as horizontally).

4.3.4 Results

See Table 4.3 for a data summary. The test-retest correlation across all three conditions is .81.

Data from Table 4.3 were analyzed using an ANOVA procedure. The ANOVA Table is given in Table 4.4. A main effect was found for FOV ($F(2,38) = 6.2; \ p < .01$). On Tukey’s procedure, the difference between the 48° and 16° FOV conditions was significant ($p < .01$) as was the difference between the 48° and 32° conditions ($p < .01$). The difference between the 32° and 16° FOV conditions was not significant. There was a trend for increasing reported presence over time ($F(1,19) = 3.4; \ p < .10$).

While there is a main effect for highest reported presence in the widest FOV condition, about a third of the participants did not follow this pattern. Five participants (6, 8, 11, 12, 14) reported highest presence not at the widest FOV. An additional two participants (10,18) reported that the widest FOV produced the same presence as at least one of the narrower two FOV’s. For all of these seven, the narrowest FOV resulted in the same or greater reported presence as the other two conditions.

4.3.5 Discussion

Despite the first and second reported presence ratings for each condition having been taken within minutes of each other, there was significant variation (.81 correlation). This is indicative of the volatility of reported presence.
Table 4.3: Reported Presence Data for Experiment AIE1

<table>
<thead>
<tr>
<th>Id</th>
<th>16° (1)</th>
<th>16° (2)</th>
<th>32° (1)</th>
<th>32° (2)</th>
<th>48° (1)</th>
<th>48° (2)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>3</td>
<td>5</td>
<td>5</td>
<td>5</td>
<td>6</td>
<td>6</td>
</tr>
<tr>
<td>2</td>
<td>3</td>
<td>2</td>
<td>3</td>
<td>3</td>
<td>4</td>
<td>4</td>
</tr>
<tr>
<td>3</td>
<td>2</td>
<td>2</td>
<td>4</td>
<td>5</td>
<td>6</td>
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<td>1</td>
<td>1</td>
<td>1</td>
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</tr>
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<td>20</td>
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<td>1</td>
<td>2</td>
<td>1.5</td>
<td>3.5</td>
<td>1.5</td>
</tr>
<tr>
<td></td>
<td>3.3(1.8)</td>
<td>3.7(1.9)</td>
<td>3.5(1.3)</td>
<td>3.9(1.4)</td>
<td>4.8(1.3)</td>
<td>4.8(1.6)</td>
</tr>
</tbody>
</table>

*Id* is the participant number. The last 6 columns give the first and second reported presence rating (1—7 scale) for the 16°, 32°, and 48° FOV conditions, respectively. The final row gives the mean and (in parentheses) standard deviation for each column.
Table 4.4: Experiment AIE1 ANOVA Table for Reported Presence Data

<table>
<thead>
<tr>
<th>Source</th>
<th>Sum of Squares</th>
<th>df</th>
<th>Mean Square</th>
<th>F</th>
<th>Sig.</th>
</tr>
</thead>
<tbody>
<tr>
<td>TREAT</td>
<td>37.4</td>
<td>2</td>
<td>18.7</td>
<td>6.2</td>
<td>p &lt; .01</td>
</tr>
<tr>
<td>SESSION</td>
<td>2.4</td>
<td>1</td>
<td>2.4</td>
<td>3.4</td>
<td>p &lt; .10</td>
</tr>
<tr>
<td>TREAT x SESSION</td>
<td>1.3</td>
<td>2</td>
<td>.6</td>
<td>1.5</td>
<td>p &gt; .10</td>
</tr>
<tr>
<td>P</td>
<td>135.8</td>
<td>19</td>
<td>7.1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>TREAT x P</td>
<td>112.4</td>
<td>38</td>
<td>3.0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>SESSION x P</td>
<td>12.8</td>
<td>19</td>
<td>.7</td>
<td></td>
<td></td>
</tr>
<tr>
<td>TREAT x SESSION x P</td>
<td>15.8</td>
<td>38</td>
<td>.4</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>318.0</td>
<td>119</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

ANOVA table for reported presence data from Experiment AIE1. “TREAT” is the treatment condition with 3 levels (16°, 32°, and 48° FOV); “SESSION” is the session number with 2 levels, and “P” is participants with 20 levels. TREAT and SESSION were each tested by their interaction with P. The TREAT x SESSION interaction was tested by TREAT x SESSION x P.
The over-all reported presence difference in favor of the $48^\circ$ condition, and the lack of difference between the two narrower conditions, is consistent with a common belief in the VE community that one approaches a “presence threshold” at about $60^\circ$ FOV.

However, about a third of the participants did not rate the widest FOV condition as having higher presence than the other two conditions. This may reflect a foreground occlusion effect (see Section 3.3.4): at the narrowest FOV, the moving scene may have appeared more distant and consequently a more salient rest frame. It would be interesting to apply the same protocol to the study of 3 wider FOV’s, such as $60^\circ$, $80^\circ$ and $100^\circ$, where the boundary is less noticeable and a foreground occlusion effect is less likely to occur.

Two pilot studies were conducted which examined a visual-inertial nulling measure for the same 3 FOV conditions. These are described in Section B.2. A primary purpose of the research described in this chapter was to measure a main effect for treatment with the nulling measure in agreement with prediction and reported presence. Because of the ambiguity in response to the three FOV conditions described above, it was decided that a different set of conditions would provide a better opportunity to establish the nulling measure. For this reason, the pilot studies described in Section B.2 were not pursued. Instead, a meaningful/random manipulation was examined, as described below.

4.4 Experiment AIE2: Meaningful/Random

4.4.1 Introduction

Experiment AIE1, which studied $16^\circ$, $32^\circ$ and $48^\circ$ FOV conditions, did not show a uniform pattern in the reported presence data. Nor was there a uniform pattern in the visual-inertial nulling data for these conditions, as reported in Section B.2. In order to test whether a clear main effect for both measures could be found in the predicted
direction, it was decided to study a different manipulation. The manipulation chosen was to compare a meaningful to a random scene. It was hypothesized that the meaningful condition would produce higher values on both the nulling and reported presence measures.

This meaningful/random manipulation was motivated in part by Experiment CogE1 (see Appendix A), which showed a main effect in the direction of higher reported presence for meaningful as compared to meaningless stimuli. Unlike the meaningful/meaningless manipulation of Experiment CogE1, the meaningful/random manipulation studied here affects low-level perceptual factors, such as number and distribution of edges.

4.4.2 Summary

See Table 4.5.

4.4.3 Methods

There were 12 adult participants (9 male, 3 female) all but 1 naive to the experimental hypothesis. Six reported more than 10 minutes prior experience with virtual environments. Due to the availability of funds, and to compensate participation near the end of an academic term, the last five participants (28, 29, 30, 31 and 32) were paid $10/session. General data about participants are given in Table 4.6.

For general methods, including the image used, see Section 4.2. As with Experiment AIE1, participants were given a one-minute pre-exposure to each condition, in random order, during which they were asked to examine the scene and gather their impressions. Per-exposure presence ratings were then taken for each condition in an independent random order. Subsequently, visual-inertial cross-over amplitudes were found according to the procedure in Section 4.2. Participants were asked to attend to the visual scene while signaling the perceived inertial endpoints of their motion.
Table 4.5: Experiment AIE2: Meaningful/Random (Nulling Measure)

<table>
<thead>
<tr>
<th>Background</th>
<th>Investigated the effect of a meaningful/random manipulation on the reported presence and nulling measures.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hypothesis</td>
<td>Both measures will record higher values for the meaningful condition.</td>
</tr>
<tr>
<td>Methods</td>
<td>A meaningful and random scene were compared, both at 48° FOV. There were two exposures to each condition for each measure. A +90° vection-inertial phase angle was used on all nulling measure trials.</td>
</tr>
<tr>
<td>Results</td>
<td>The test-retest correlation for both measures was about .80. The nulling measure found the predicted effect (p &lt; .05). There was a trend for reported presence in the predicted direction (p &lt; .10).</td>
</tr>
<tr>
<td>Conclusions</td>
<td>For the meaningful/random conditions, the nulling measure is self-consistent and agrees with prediction and a trend in the reported presence data.</td>
</tr>
</tbody>
</table>

A 48° FOV was used (the widest the HMD allowed). In the “random” condition, the location of each pixel in the image was randomized. The “meaningful” condition was the image as originally taken\(^{16}\).

The experiment was run in two sessions, each comparing the meaningful to the random condition with both nulling and reported presence dependent measures. The two sessions were procedurally identical, except that an Embedded Figures Test was administered following one of these sessions and the introduction was not repeated.

\(^{16}\) Thus, the “meaningful” condition from the current experiment was identical to the “48°” condition from Experiment AIE1.
Table 4.6: Participant Overview for Experiment AIE2

<table>
<thead>
<tr>
<th>Id</th>
<th>Gn</th>
<th>Age</th>
<th>Prev</th>
<th>EFT</th>
</tr>
</thead>
<tbody>
<tr>
<td>21</td>
<td>M</td>
<td>36</td>
<td>1</td>
<td>24</td>
</tr>
<tr>
<td>22</td>
<td>M</td>
<td>32</td>
<td>0</td>
<td>15</td>
</tr>
<tr>
<td>23</td>
<td>F</td>
<td>28</td>
<td>1</td>
<td>37</td>
</tr>
<tr>
<td>24</td>
<td>M</td>
<td>33</td>
<td>0</td>
<td>21</td>
</tr>
<tr>
<td>25</td>
<td>M</td>
<td>55</td>
<td>1</td>
<td>15</td>
</tr>
<tr>
<td>26</td>
<td>M</td>
<td>23</td>
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</tr>
<tr>
<td>27</td>
<td>M</td>
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<td>30</td>
</tr>
<tr>
<td>28</td>
<td>M</td>
<td>44</td>
<td>1</td>
<td>29</td>
</tr>
<tr>
<td>29</td>
<td>F</td>
<td>28</td>
<td>1</td>
<td>7</td>
</tr>
<tr>
<td>30</td>
<td>F</td>
<td>44</td>
<td>0</td>
<td>38</td>
</tr>
<tr>
<td>31</td>
<td>M</td>
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<td>0</td>
<td>26</td>
</tr>
<tr>
<td>32</td>
<td>M</td>
<td>24</td>
<td>0</td>
<td>10</td>
</tr>
</tbody>
</table>

*Id* is the participant number. *Gn* gives the gender, *Age* the age in years, and *Prev* is “1” if the participant had more than 10 minutes of prior experience in virtual environments, “0” otherwise. *EFT* gives Embedded Figures Test scores.
Each session began by obtaining one per-exposure reported presence rating for each condition according to the procedure described in Section 4.2.2.

4.4.4 Results

The ANOVA Table for the cross-over data is given in Table 4.8. A main effects was found for treatment, with the “meaningful” condition higher than the “random” condition ($F(1,11) = 8.7; p < .05$).

The ANOVA Table for the reported presence data is given in Table 4.9. A trend was found for treatment, with the “meaningful” condition higher than the “random” condition ($F(1,11) = 2.7; p < .10$).

The test-retest correlation between sessions is .83 for the visual-inertial nulling measure and .80 for the reported presence measure.

Table 4.10 gives the correlation between the EFT scores for each participant and the mean across sessions of the meaningful and random data for both measures. At the current sample size, none of these correlations are significantly different from zero ($p < .05$).

The correlation of the cross-over data with the reported presence data for each subject is .06$^{17}$.

The correlation of the difference between conditions for the visual-inertial nulling measure with the difference between conditions for the reported presence measure is .38$^{18}$. There is a trend for this correlation being significantly different from zero ($p < .07$).

In the post-experiment debrief, 10 of the 12 participants reported (incorrectly) believing that the vection-inertial phase angle varied between trials. One was uncertain

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$^{17}$ This was computed by comparing all data between the two measures with matched participant identifier, treatment condition, and session number.

$^{18}$ This was computed by finding the difference across treatment conditions for matched participants and session numbers, then correlating these differences across measures.
Table 4.7: Nulling and Reported Presence Data for Experiment AIE2

<table>
<thead>
<tr>
<th>Id</th>
<th>Cross-Over (°/sec)</th>
<th>Reported Presence (1-7)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1st Session</td>
<td>2nd Session</td>
</tr>
<tr>
<td></td>
<td>MCO</td>
<td>RCO</td>
</tr>
<tr>
<td>21</td>
<td>35</td>
<td>35</td>
</tr>
<tr>
<td>22</td>
<td>1.5</td>
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<td>23</td>
<td>9</td>
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<td>31</td>
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<td>13.2</td>
</tr>
<tr>
<td>STD</td>
<td>13.2</td>
<td>13.0</td>
</tr>
</tbody>
</table>

Data from Experiment AIE2. Cross-over gives the inertial amplitude at which participants switch between visual and inertial dominance. (These data are the mean of cross-over ranges, as described in Section 4.2, except where an upper bound was not found. In these cases, the lower bound of 35°/sec was used.) Higher values indicate more visual capture. Reported Presence gives the participant’s perceived report of their sense of “being in” the visual scene. Id is the participant number, equivalent to the participant numbers in Table 4.6. MCO and RCO give the cross-over amplitudes for the meaningful and random conditions, respectively. MRP and RRP give the reported presence ratings for the meaningful and random conditions, respectively. The bottom two rows give the mean and STD for each column.
Table 4.8: Experiment AIE2 ANOVA Table for Cross-Over Data

<table>
<thead>
<tr>
<th>Source</th>
<th>Sum of Squares</th>
<th>df</th>
<th>Mean Square</th>
<th>F</th>
<th>Sig.</th>
</tr>
</thead>
<tbody>
<tr>
<td>TREAT</td>
<td>56.3</td>
<td>1</td>
<td>56.3</td>
<td>8.7</td>
<td>p &lt; .05</td>
</tr>
<tr>
<td>SESSION</td>
<td>14.1</td>
<td>1</td>
<td>14.1</td>
<td>0.3</td>
<td>p &gt; .10</td>
</tr>
<tr>
<td>TREAT x SESSION</td>
<td>1.3</td>
<td>1</td>
<td>1.3</td>
<td>0.2</td>
<td>p &gt; .10</td>
</tr>
<tr>
<td>P</td>
<td>6402.4</td>
<td>11</td>
<td>582.0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>TREAT x P</td>
<td>71.0</td>
<td>11</td>
<td>6.5</td>
<td></td>
<td></td>
</tr>
<tr>
<td>SESSION x P</td>
<td>555.3</td>
<td>11</td>
<td>50.5</td>
<td></td>
<td></td>
</tr>
<tr>
<td>TREAT x SESSION x P</td>
<td>64.8</td>
<td>11</td>
<td>5.9</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>7165.3</td>
<td>47</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

ANOVA table for cross-over data from Experiment AIE2. “TREAT” is the treatment condition with 2 levels (meaningful/random), “SESSION” is the session number with 2 levels, and “P” is participants with 12 levels. TREAT and SESSION were each tested by their interaction with P. The TREAT x SESSION interaction was tested by TREAT x SESSION x P.
Table 4.9: Experiment AIE2 ANOVA Table for Reported Presence Data

<table>
<thead>
<tr>
<th>Source</th>
<th>Sum of Squares</th>
<th>df</th>
<th>Mean Square</th>
<th>F</th>
<th>Sig.</th>
</tr>
</thead>
<tbody>
<tr>
<td>TREAT</td>
<td>3.0</td>
<td>1</td>
<td>3.0</td>
<td>2.7</td>
<td>p &lt; .10</td>
</tr>
<tr>
<td>SESSION</td>
<td>.3</td>
<td>1</td>
<td>.3</td>
<td>.3</td>
<td>p &gt; .10</td>
</tr>
<tr>
<td>TREAT x SESSION</td>
<td>.3</td>
<td>1</td>
<td>.3</td>
<td>.6</td>
<td>p &gt; .10</td>
</tr>
<tr>
<td>P</td>
<td>119.0</td>
<td>11</td>
<td>10.8</td>
<td></td>
<td></td>
</tr>
<tr>
<td>TREAT x P</td>
<td>12.0</td>
<td>11</td>
<td>1.1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>SESSION x P</td>
<td>9.7</td>
<td>11</td>
<td>.9</td>
<td></td>
<td></td>
</tr>
<tr>
<td>TREAT x SESSION x P</td>
<td>5.7</td>
<td>11</td>
<td>.5</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>150.0</td>
<td>47</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

ANOVA table for cross-over data from Experiment AIE2. “TREAT” is the treatment condition with 2 levels (meaningful/random), “SESSION” is the session number with 2 levels, and “P” is participants with 12 levels. TREAT and SESSION were each tested by their interaction with P. The TREAT x SESSION interaction was tested by TREAT x SESSION x P.

Table 4.10: Correlations Between EFT Scores and the Two Dependent Measures

<table>
<thead>
<tr>
<th></th>
<th>Cross-Over</th>
<th>Reported Presence</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Meaningful</td>
<td>Random</td>
</tr>
<tr>
<td>EFT</td>
<td>.45(.14)</td>
<td>.42(.18)</td>
</tr>
</tbody>
</table>

The correlation between the Embedded Figures Test scores and the cross-over and reported presence data for each of the meaningful and random conditions. The significance of each correlation is given in parentheses, for the null hypothesis that the correlation is zero. While the cross-over correlations appear higher, none of these correlations are significantly different from zero at the current sample size.
and one believed (correctly) that the phase angle was always the same.

### 4.4.5 Discussion

The visual-inertial nulling measure found a main effect for treatment in the predicted direction of meaningful higher than random ($p < .05$). The reported presence measure showed a trend in the same direction ($p < .10$). Both measures showed reasonable test-retest reliability (.83 and .80, respectively).

It is not surprising that no relationship (.06 correlation) was found between the magnitude of the cross-over data and the magnitude of reported presence. This is consistent with the lack of a standard scale, between participants, governing how to assign numbers to mental states. However, there is a weak relationship (.38 correlation) between differences across treatment conditions across the two measures. Thus, participants who reported a large difference in presence between the two conditions showed a weak tendency to exhibit a corresponding large difference in the nulling measure.

While the current sample size did not show statistical significance, the correlation of the visual-inertial nulling measure with the EFT scores appears to be higher than the correlation of the reported presence measure with the EFT scores. This is consistent with the suggestion that the visual-inertial nulling measure is more closely related to field dependency, a factor which would be expected to influence between-subject variation in presence levels. This implies that the between-subject variation in the visual-inertial milling measure may be more accurate than the between-subject variation in the reported presence measure at recording real differences in presence.

A concern was that a learning effect would result from using the same vection-inertial phase angle for all trials. This concern appears to be unfounded. Ten out of 12 of the participants believed that the phase angle varied between trials, with one more uncertain. (Additionally, all 4 of the participants in Pilot Study AIP4 believed the phase angle varied between trials.) Nor was there a main effect for session number.
in the ANOVA.

Why did participants not notice the constant phase relationship? One possibility is as follows. As the inertial amplitude dropped, the visual influence on the sense of motion increased, which made it more difficult to distinguish the inertial from the visual self-motion cues. This may have been interpreted as a decrease in the vection-inertial phase difference. Consistent with this (as mentioned at the end of Section 4.2.1), participants did not tend to make a sudden jump from inertial to visual dominance, but rather approached the cross-over by signaling progressively further from the inertial peak as the inertial amplitude was lowered.

The continuous approach to the cross-over amplitude is supportive of the view that the sense of presence in an environment is a gradated, rather than all-or-nothing, phenomenon. It is also consistent with research on visual-proprioceptive discrepancies. Welch and Warren [109], reviewing the literature, report that “visual bias of proprioception is not an all-or-none phenomenon.”

4.4.6 Conclusion

This preliminary research has shown that the visual-inertial nulling measure is capable of finding a main effect in the predicted direction which agrees with a trend in reported presence scores, and that the test-retest reliabilities for the two measures are similar. It finds a weak trend for a stronger relationship between the visual-inertial nulling measure and field dependency (as measured by the Embedded Figures Test) than between reported presence and field dependency.

A nulling presence measure has considerable advantages over a presence measure based on self-report. Humans were evolved to make perceptual judgments. We rarely articulate spatial judgments; however our action reveals those “judgments”. Spatial perception supports action, primarily by representing what actions the environment will permit. We were not evolved to rate presence on a numeric scale.

Because the nulling measure is more deeply rooted than reported presence, cross-
over amplitudes found in different experiments may be less distorted by anchor ef-
fects than are reported presence ratings. This would allow knowledge to be built up systematically by pooling data across experiments, rather than being limited to within-experiment comparisons.

The prediction that the nulling measure is less prone to anchor effects than the reported presence measure could be tested by comparing a condition A to a condition B in one experiment, and by comparing condition A to a quite different condition C in a second experiment with different participants. The prediction would be that condition A would have similar values in the two experiments on the nulling measure, but significantly different values in the two experiments on the reported presence measure.

Finally, a measure which is much more convenient than the visual-inertial nulling measure described here, but which preserves its desirable properties, may be possible. This measure would be based on the induced-motion of a background grid, as reported in Appendix D and discussed in Chapter 8.
Chapter 5

AREA II: PRESENCE MANIPULATIONS

5.1 Introduction

In the previous chapter, the measurement of selected rest frames through visual-inertial nulling was examined as a means to evaluate the sense of presence. In this chapter, the manipulation of selected rest frames is studied as a means to alter the sense of presence. Specifically, this chapter studies the effect of foreground occlusions\(^1\).

The following questions are addressed in this chapter.

1. Can a foreground occlusion increase reported presence?

2. Can a performance measure be found for the effect of a foreground occlusion?

Experiment AIIIE1 and Experiment AIIIE2 sought to measure the effect of a foreground occlusion on reported presence. Research on a performance measure for foreground occlusions is discussed in Appendix C, in reference to inside-out displays.

\(^1\) See Section 3.7.6 for background. Related pilot studies and an experiment on inside-out displays are described in Appendix C. The description of Experiments AIIIE1 and AIIIE2 borrows from [83] and [82]. While I was the lead investigator, this research was carried out in collaboration with Dr. Hunter Hoffman.
5.2 Experiment AIEE1: Foreground Occlusions and Reported Presence I

5.2.1 Introduction

Previous research had suggested that a foreground occlusion can increase vection. Experiment AIEE1 addressed the question of whether it can also increase reported presence. This question is important for both theoretical and practical reasons. The theoretical reason is that the RFC and the presence hypothesis predict a close relationship between vection and presence. Specifically, vection results from one aspect of the selected rest frame (the implied self-motion) whereas presence reflects the selected rest frame in general. Hence, if foreground occlusions increase vection (for possible reasons discussed in Section 3.7.6), then it follows that foreground occlusions should also increase presence. One purpose of Experiment AIEE1 was to test this theoretical prediction.

The practical reason for investigating whether foreground occlusions affect the sense of presence has to do with HMD design. Traditionally, it has been believed that a wide FOV is necessary to induce a strong sense of presence. There is a trade-off between FOV and resolution. Hence, if one wants to increase the sense of presence by increasing the FOV, one needs to lower the resolution. If a foreground occlusion mounted inside an HMD can increase the sense of presence, then it may be possible to have a high level of presence at a low FOV. Experiment AIEE1 investigates this possibility as well.

5.2.2 Summary

See Table 5.1.
### Table 5.1: Experiment AIIE1: Foreground Occlusions and Reported Presence

<table>
<thead>
<tr>
<th><strong>Background</strong></th>
<th>Foreground occlusions have been shown to increase reported vection. If presence and vection are closely related, foreground occlusions should also increase reported presence.</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Hypothesis</strong></td>
<td>Foreground occlusions increase reported presence compared to the same FOV without a foreground occlusion.</td>
</tr>
<tr>
<td><strong>Methods</strong></td>
<td>The same 60° FOV was provided in an HMD either with or without a foreground occlusion mounted in front of the screen. Reported presence was assessed with a presence questionnaire following 2.5 minute exposures to each condition.</td>
</tr>
<tr>
<td><strong>Results</strong></td>
<td>Reported presence was higher in the foreground occlusion condition (p &lt; .01).</td>
</tr>
<tr>
<td><strong>Conclusions</strong></td>
<td>The results support the prediction that foreground occlusions can increase reported presence.</td>
</tr>
</tbody>
</table>

#### 5.2.3 Methods

There were 26 adult volunteers (19 male, 7 female). The experimental hypothesis. Three reported more than 10 minutes prior experience with virtual environments. The participants are summarized in Table 5.2.

See Section 3.7 for an overview of the equipment and Section 3.8.1 for a discussion of the presence questionnaire. Participants were exposed to the “Sharkworld” environment run on a Division ProVision 100 using a dVisor HMD. A foreground occlusion was provided with a pair of Lucas Products “Super Sunnies” tanning goggles with the central ultra-violet protector removed. As the tanning goggles were worn directly over the eyes and blocked peripheral vision, they removed visual cues surrounding the screen in the HMD. Thus, the tanning goggles met the “foreground
### Table 5.2: Participant Overview for Experiment A1E1

<table>
<thead>
<tr>
<th>Id</th>
<th>Gn</th>
<th>Prev</th>
<th>Id</th>
<th>Gn</th>
<th>Prev</th>
</tr>
</thead>
<tbody>
<tr>
<td>33</td>
<td>M</td>
<td>0</td>
<td>46</td>
<td>M</td>
<td>0</td>
</tr>
<tr>
<td>34</td>
<td>F</td>
<td>0</td>
<td>47</td>
<td>F</td>
<td>0</td>
</tr>
<tr>
<td>35</td>
<td>M</td>
<td>0</td>
<td>48</td>
<td>F</td>
<td>0</td>
</tr>
<tr>
<td>36</td>
<td>M</td>
<td>1</td>
<td>49</td>
<td>F</td>
<td>0</td>
</tr>
<tr>
<td>37</td>
<td>M</td>
<td>0</td>
<td>50</td>
<td>F</td>
<td>0</td>
</tr>
<tr>
<td>38</td>
<td>M</td>
<td>1</td>
<td>51</td>
<td>M</td>
<td>0</td>
</tr>
<tr>
<td>39</td>
<td>M</td>
<td>0</td>
<td>52</td>
<td>M</td>
<td>0</td>
</tr>
<tr>
<td>40</td>
<td>M</td>
<td>0</td>
<td>53</td>
<td>M</td>
<td>0</td>
</tr>
<tr>
<td>41</td>
<td>M</td>
<td>0</td>
<td>54</td>
<td>M</td>
<td>0</td>
</tr>
<tr>
<td>42</td>
<td>M</td>
<td>0</td>
<td>55</td>
<td>M</td>
<td>0</td>
</tr>
<tr>
<td>43</td>
<td>M</td>
<td>0</td>
<td>56</td>
<td>F</td>
<td>0</td>
</tr>
<tr>
<td>44</td>
<td>M</td>
<td>0</td>
<td>57</td>
<td>F</td>
<td>0</td>
</tr>
<tr>
<td>45</td>
<td>M</td>
<td>0</td>
<td>58</td>
<td>M</td>
<td>1</td>
</tr>
</tbody>
</table>

*Id* is the participant number, *Gn* gives the gender, and *Prev* is “1” if the participant had more than 10 minutes of prior experience in virtual environments, “0” otherwise. Age data was not collected for this experiment, beyond noting that all participants were over 18.
occlusion” definition of blocking out all cues at the same or greater distance than the display\(^2\).

The tanning goggles limited the FOV to about \(60^\circ\). A matching FOV for the non-foreground occlusion condition was provided by masking the HMD screen with construction paper affixed directly to the screen’s surface.

Each participant was run for 2.5 minutes in each of the foreground occlusion and non-foreground occlusion conditions with the condition order counterbalanced across participants. They were shown how to catch moving sharks with a virtual net attached to the hand. However, their activity in the virtual environment was not constrained by any particular task. After viewing both conditions, participants completed a presence questionnaire.

Before filling out the presence questionnaire, but after exposure to the virtual environment, participants were introduced to the idea of presence with the following paragraph.

Experiencing a virtual world can lead to a conflict in where you focus your attention. For instance, in the Sharkworld, you may feel like you are in the ocean, near a shark-infested shipwreck. At the same time, you may be aware of the contradictory fact that you are just standing in the laboratory, wearing a virtual reality helmet. The following questions assess the extent to which you felt “immersed” in the virtual world, and the relative intensity of this feeling when wearing the tanning goggles compared to when the screen was masked with paper. There are no “correct” answers, please make your ratings as honestly as possible. Circle one of the numbers.

\(^2\) Actually, due to the design of the dVisor and of the tanning goggles, part of the nasal edge of the screen was visible in the foreground occlusion condition. The effect found below would be predicted to have been even stronger if the foreground occlusion had perfectly blocked the screen boundary.
Results

Statistical analysis used a paired, two-tailed, non-parametric Wilcoxon signed-rank test. The responses averaged across all 5 presence questions were larger ($Z = 3.1$, $p = .002$) for foreground occlusion ($M = 4.2$, $SD = 1.1$) than for non-foreground occlusion ($M = 3.3$, $SD = 1.0$). When the responses to each question were analyzed separately, significant differences between viewing conditions were found for all 5 questions ($Z = 2.69$, $p = .007$; $Z = 3.26$, $p = .001$; $Z = 2.49$, $p = .01$; $Z = 2.79$, $p = .005$; and $Z = 2.36$, $p = .02$, respectively).

Discussion

The results of Experiment AIIE1 support the hypothesis that foreground occlusions increase reported presence. Further, they suggest that a foreground occlusion mounted in an HMD may be of practical benefit for increasing presence.

While Experiment AIIE1 found a large difference between conditions, the possibility existed that the results were due to subtle cues picked up from the experimenters. Experiment AIIE2 was a replication of Experiment AIIE1 which controlled for this possibility, by using an experimenter blind to the hypothesis.

5.3 Experiment AIIE2: Foreground Occlusions and Reported Presence II

5.3.1 Introduction

Experiment AIIE2 was run in the same manner as Experiment AIIE1 except that additional steps were taken to remove possible experimental bias. It was hypothesized that the foreground occlusion would increase reported presence.
5.3.2 Summary

See Table 5.3.

Table 5.3: Experiment AIE2: Foreground Occlusions and Reported Presence II

<table>
<thead>
<tr>
<th><strong>Background</strong></th>
<th>Experiment AIE1 found an effect of foreground occlusion on reported presence. However, demand characteristics may have played a role.</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Hypothesis</strong></td>
<td>Foreground occlusions increase reported presence compared to the same FOV without a foreground occlusion.</td>
</tr>
<tr>
<td><strong>Methods</strong></td>
<td>The experimenter was naive to the hypothesis. The same 60° FOV was provided in an HMD either with or without a foreground occlusion mounted in front of the screen. Reported presence was assessed with a presence questionnaire following 2.5 minute exposures to each condition.</td>
</tr>
<tr>
<td><strong>Results</strong></td>
<td>Reported presence was higher in the foreground occlusion condition (p &lt; .04).</td>
</tr>
<tr>
<td><strong>Conclusions</strong></td>
<td>The results support the prediction that foreground occlusions can increase reported presence.</td>
</tr>
</tbody>
</table>

5.3.3 Methods

There were 13 adult volunteers (9 male, 4 female). One reported more than 10 minutes prior experience with virtual environments. The participants are summarized in Table 5.4.

The procedure for Experiment AIE2 was identical to Experiment AIE1 except for two modifications. Firstly, Experiment AIE2 was run using a double-blind procedure in which the experimenter (as well as the participants) was kept unfamiliar
Table 5.4: Participant Overview for Experiment AIIE2

<table>
<thead>
<tr>
<th>Id</th>
<th>Gn</th>
<th>Prev</th>
</tr>
</thead>
<tbody>
<tr>
<td>59</td>
<td>F</td>
<td>0</td>
</tr>
<tr>
<td>60</td>
<td>M</td>
<td>0</td>
</tr>
<tr>
<td>61</td>
<td>M</td>
<td>1</td>
</tr>
<tr>
<td>62</td>
<td>M</td>
<td>0</td>
</tr>
<tr>
<td>63</td>
<td>M</td>
<td>0</td>
</tr>
<tr>
<td>64</td>
<td>F</td>
<td>0</td>
</tr>
<tr>
<td>65</td>
<td>M</td>
<td>0</td>
</tr>
<tr>
<td>66</td>
<td>M</td>
<td>0</td>
</tr>
<tr>
<td>67</td>
<td>F</td>
<td>0</td>
</tr>
<tr>
<td>68</td>
<td>M</td>
<td>0</td>
</tr>
<tr>
<td>69</td>
<td>M</td>
<td>0</td>
</tr>
<tr>
<td>70</td>
<td>F</td>
<td>0</td>
</tr>
<tr>
<td>71</td>
<td>M</td>
<td>0</td>
</tr>
</tbody>
</table>

*Id* is the participant number, *Gn* gives the gender. *Prev* is “1” if the participant had more than 10 minutes of prior experience in virtual environments, “0” otherwise. Age data was not collected for this experiment, beyond noting that all participants were over 18.
with the hypothesis. The experimenter was a new visiting student from Europe. He administered the questionnaires in sealed envelopes and was not shown their content, or allowed to discuss the experiment, until after it was concluded. In addition, participants were instructed not to discuss the experiment with the experimenter.

Secondly, the order of presence questions about the two conditions was randomized across participants.

5.3.4 Results

Statistical analysis used a paired, two-tailed, non-parametric Wilcoxon signed-rank test. For Experiment AIIIE2 (with half the number of participants of Experiment AIIIE1) the responses averaged across all 5 questions were larger ($Z = 2.1$, $p = .03$) for foreground occlusion ($M = 4.3$, $SD = .93$) than for non-foreground occlusion ($M = 3.4$, $SD = .93$).

5.3.5 Discussion

The results from Experiment AIIIE2 appear to rule out demand characteristics as a possible explanation of the results for Experiment AIIIE1. The results from Experiments AIIIE1 and AIIIE2 are consistent with the prediction of Section 3.7.6 that foreground occlusions increase presence.

5.4 Inside-Out Displays and Foreground Occlusions

Section 3.3.4 suggested that foreground occlusions might reduce control reversals associated with inside-out displays. Approximately 3,000 trials were carried out to address this question. As no effect was found, this line of investigation is reported in abbreviated form in Appendix C.
Chapter 6

AREA III: MOTION SICKNESS

Praise the sea, but keep on the land.

— Herbert

6.1 Introduction

The previous two chapters were intended to study the measurement and manipulation of selected rest frames. This chapter is concerned with the consequences when a consistent selected rest frame can not be formed\(^1\). It examines a situation common with simulators, in which the visual cues imply self-motion, but the inertial cues do not.

The following questions are addressed in this chapter.

1. Can an independent visual background (IVB) in agreement with inertial cues reduce reported simulator sickness and related side-effects?

2. If so, can it do so without reducing the subjective impact of the scene?

3. Can an IVB be effective even when attention is directed to the visual foreground, in which visual self-motion cues disagree with the inertial cues?

\(^1\) See Section 3.3.5 for background, and Section 3.7 for a description of the equipment. This chapter borrows from [80] and [81]. While I was the lead investigator, this research was carried out in collaboration with Mark Draper.
Experiment AIIIIE1 explored questions 1 and 2, above. Experiment AIIIIE2 was a follow-up study which added a visual task which forced attention into the visual foreground. This allowed the 3rd question to be addressed as well.

Both Experiment AIIIIE1 and Experiment AIIIIE2 involved a “low-end” virtual environment with limited FOV. A brief pilot study involving a “high-end” driving simulator, intended as a motion sickness experiment, is described in Appendix D because of its possible implications for an improved presence measure. See Chapter 7 for a discussion.

6.2 Experiment AIIIIE1: Independent Visual Background for Low-End Systems I

6.2.1 Introduction

Experiment AIIIIE1 was the initial study of the effectiveness of an IVB for reducing simulator side-effects. A low-end system was used, comparing the see-through (IVB) and occluded (non-IVB) modes of a Virtual i-O HMD. A circularvection stimulus was provided in both conditions. Illumination levels were such that the IVB was rated by participants as being less visible than the vection stimulus. It was hypothesized that the IVB condition would produce lower simulator side-effects than the non-IVB condition.

6.2.2 Summary

See Table 6.1.

6.2.3 Methods

There were 15 adult volunteers (10 male, 5 female). Twelve reported more than 10 minutes prior experience with virtual environments. The participants are summarized in Table 6.2.
Table 6.1: Experiment AIIIIE1: Independent Visual Background I (Low-End)

<table>
<thead>
<tr>
<th>Background</th>
<th>Motion sickness may arise from conflicting rest frames, rather than from conflicting motion cues <em>per se</em>. The visual rest frame is heavily influenced by the visual background.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hypothesis</td>
<td>A visual background in agreement with inertial cues should reduce simulator side-effects, even if the visual foreground is not in agreement with inertial cues.</td>
</tr>
<tr>
<td>Methods</td>
<td>A circularvection stimuli was provided both with and without a stationary visual background. Measures included per-exposure postural instability and post-exposure reported simulator sickness.</td>
</tr>
<tr>
<td>Results</td>
<td>Both postural instability ((p &lt; .03)) and SSQ ((p &lt; .05)) were significantly lower with a stationary visual background.</td>
</tr>
<tr>
<td>Conclusions</td>
<td>The results support the hypothesis.</td>
</tr>
</tbody>
</table>

A pre-exposure SSQ was administered to check for pre-existing nausea or related symptoms. No participants or data were removed on this basis.

See Section 3.7 for a description of the equipment. The experiment was conducted as a within-subjects design. The order of conditions was counter-balanced across participants.

A circular motion visual stimulus was created by placing a videocamera on a tripod in an open plaza on the University of Washington campus and continuously rotating the camera through 360° in yaw with a period of six seconds. The location was picked for visual salience, having a variety of sharp edges and both vertical and horizontal features. The angular velocity of 60°/sec was picked in accordance with literature indicating that motion sickness peaks at this value [30]. Other sources
Table 6.2: Participant Overview for Experiment AIIIIE1

<table>
<thead>
<tr>
<th>Id</th>
<th>Gn</th>
<th>Age</th>
<th>Prev</th>
</tr>
</thead>
<tbody>
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<td>F</td>
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<td>1</td>
</tr>
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<td>74</td>
<td>M</td>
<td>22</td>
<td>1</td>
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<td>75</td>
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<td>42</td>
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</tr>
<tr>
<td>86</td>
<td>M</td>
<td>29</td>
<td>1</td>
</tr>
</tbody>
</table>

*Id* is the participant number, *Gn* gives the gender, *Age* the age in years, and *Prev* is “1” if the participant had more than 10 minutes of prior experience in virtual environments, “0” otherwise.
suggest that vection increases with stimulus velocity up to about 90°/sec [20], at least for stimuli consisting of vertical stripes.

The head-mounted display (HMD) used to display the videotape was a Virtual i-O i-glasses! VTV/VPC (see Section 3.7.3 for HMD specifications). The HMD was masked so that no visual cues were available except those on or through the display. (That is, the edges of the optics and HMD were occluded.)

For each participant, there were two separate three-minute sessions in which he/she was exposed to the circular motion stimulus, one session in each of the see-through (IVB) and occluded (no IVB) modes (see Figure 3.2 on page 43). The sessions were separated by 5 minutes. During the first and third minutes of each session, participants were asked to stand in the “Sharpened Romberg” stance. This stance consists of placing one foot in front of the other, heel touching toe, weight evenly distributed between the legs, arms folded across the chest and chin up [32]. In the second minute, to avoid fatigue, participants were allowed to stand in a relaxed posture, but were instructed to continue to look forward. Half-way through the first, second and third minutes, participants were asked to roll their heads down to their right shoulder, then to their left shoulder, then return their head to the upright position. This action was intended to increase motion sickness by introducing a visual-vestibular interaction.

Participants were instructed to keep their eyes open and to look forward. They were told that they could break the Sharpened Romberg stance if necessary, but that they should get back into it as quickly as possible. Other than maintaining postural stability and looking forward, participants were not given a task in Experiment AII-E1.

A verbal rating of the relative visibility of the background in the see-through condition was recorded in the post-test questionnaire. This was intended to make sure that the IVB in the see-through condition was not simply “washing-out” the circular vection stimulus provided by the HMD. A 1–5 scale was used, with the low
end indicating that only the foreground scale was visible, and the high end indicating that only the background was visible.

Three dependent measures were recorded in Experiment AIIIIE1 to measure the effect of the IVB. The first was a measure of per-exposure ataxia: the total number of stance breaks in the first (SB1) and third (SB3) minutes of each session. A break was defined as a translation of either foot and/or an uncrossing of the arms. Participants were asked to maintain the Sharpened Romberg stance, but if a break was necessary they were to asked to get back into Sharpened Romberg as soon as possible.

The second dependent measure was the post-exposure SSQ, to record self-reported symptoms of simulator sickness.

The third dependent measure was a post-exposure rating of vection, defined in terms of the following question. “While in the virtual environment, did you get the feeling of motion (i.e., did you experience a compelling sensation of self-motion as though you were actually moving)?” The endpoints of the 1–7 scale were anchored as “not at all” and “very much so”, respectively.

6.2.4 Results

Data from one participant were not analyzed due to inability to perform the Sharpened Romberg task, particularly in the occluded condition. The data from the remaining fourteen participants are summarized in Table 6.2.4.

The stance break data passed tests of normality and homogeneity. Total stance breaks, SB1 and SB3 were analyzed with a 2-tail paired t-test. The questionnaire data, SSQ and vection ratings, were analyzed using a non-parametric, 2-tail paired Wilcoxon.

Both SSQ (p < .05) and total stance breaks (p < .03) were significantly lower in the see-through than the occluded condition. Pooling across conditions, there were significantly fewer stance breaks in SB1 than SB3 (p < .03), indicating increased ataxia as the experiment progressed. There was a weak trend for higher vection in
<table>
<thead>
<tr>
<th>Measure</th>
<th>Condition</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>See-through</td>
<td>Occluded</td>
<td></td>
</tr>
<tr>
<td>SSQ *</td>
<td>15.0(16.0)</td>
<td>18.7(24.5)</td>
<td></td>
</tr>
<tr>
<td>Total Stance Breaks *</td>
<td>4.1(4.8)</td>
<td>9.1(8.2)</td>
<td></td>
</tr>
<tr>
<td>SB1</td>
<td>1.1(1.5)</td>
<td>3.9(3.2)</td>
<td></td>
</tr>
<tr>
<td>SB3</td>
<td>3.0(3.6)</td>
<td>5.2(5.5)</td>
<td></td>
</tr>
<tr>
<td>Vection</td>
<td>3.5/7.0(1.7)</td>
<td>3.5/7.0(1.9)</td>
<td></td>
</tr>
<tr>
<td>Background Visibility</td>
<td>2.0/5.0(0.6)</td>
<td>N/A</td>
<td></td>
</tr>
</tbody>
</table>

“SSQ” is a reported simulator sickness value [55]. “SB1” and “SB3” are the total number of stance breaks in the first and third minute, respectively. For the skewed data (SSQ, vection and visibility ratings), medians are reported. Other values are means. Standard deviations are given in parentheses. “∗” implies that the difference between conditions is significant at p < .05.
the occluded condition (p < .14).

A weak trend was found for an overall order effect for total stance breaks, with the first condition more difficult (p < .13).

6.2.5 Discussion

Experiment AIIIE1 examined whether an IVB (see-through condition) could reduce simulator side-effects. The introduction of an IVB significantly reduced ataxia and SSQ ratings while viewing the vection stimulus. Given that vection ratings were not significantly lower in the see-through condition, an IVB may be able to reduce negative effects of simulators without significantly affecting the subjective impact of the virtual environment.

Two questions posed by the ataxia data from Experiment AIIIE1 are: 1. “what would the baseline number of stance breaks be without a visual stimulus?” and, 2. “was the increase in stance breaks from the first to the third minute due to a build-up of effect or due to physiological fatigue from holding the Sharpened Romberg stance?” Pilot Study AIIIP1 was conducted to examine these questions (see Appendix D). It was concluded that the baseline number of stance breaks is essentially zero, and that the increase in stance breaks from the first to the third minute was primarily due to a build-up of effect.

6.3 Experiment AIIIE2: Independent Visual Background for Low-End Systems II

6.3.1 Introduction

Four possible short-comings were identified with Experiment AIIIE1.

First, the visual background might have been simply “washing out” the vection stimulus in the CI. This seems unlikely, given that participants rated the IVB as less visible than the CI (mean rating of 2, with 1 indicating only the CI was visible, 5
indicating only the IVB was visible).

Second, performance of the head rolls by the participant often varied within and between sessions, as well as between participants.

Third, the time between sessions may not have been long enough to prevent carryover effects.

Fourth, it was possible that subjects were simply ignoring the CI in the see-through condition. An IVB is only useful if it confers value while the subject is primarily attending to the CI, where the simulator task is being performed.

Experiment AIIIIE2 was similar to Experiment AIIIIE1, with a few refinements described in the Methods section. The refinements were intended to address the above issues. Most importantly, a visual task was provided to direct attention into the visual foreground. This controlled for the degree to which participants attended to the visual foreground. It also created a stronger link to a real simulator task, in which attention would have to be focused on the visual foreground, rather than the IVB.

As with Experiment AIIIIE1, it was hypothesized that the IVB condition would produce less simulator side-effects than the non-IVB condition.

6.3.2 Summary

See Table 6.4.

6.3.3 Methods

There were 21 adult volunteers (15 male, 6 female). Four reported more than 10 minutes prior experience with virtual environments. The participants are summarized in Table 6.5.

None had participated in Experiment AIIIIE1. Participant screening was done more rigorously than in Experiment AIIIIE1. Participants were asked whether they
Table 6.4: Experiment AIIIIE2: Independent Visual Background II (Low-End)

<table>
<thead>
<tr>
<th>Background</th>
<th>Experiment AIIIIE1 found an effect for a stationary visual background reducing simulator side-effects. But this reduction might disappear if attention is forced into the visual foreground.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hypothesis</td>
<td>A visual background in agreement with inertial cues should reduce simulator side-effects, even if the visual foreground is not in agreement with inertial cues.</td>
</tr>
<tr>
<td>Methods</td>
<td>A circularvection stimuli was provided both with and without a stationary visual background. Measures included per-exposure postural in stability and post-exposure reported simulator sickness. A visual task forced attention into the visual foreground.</td>
</tr>
<tr>
<td>Results</td>
<td>Postural instability was significantly lower with a stationary visual background (p &lt; .03).</td>
</tr>
<tr>
<td>Conclusions</td>
<td>The results support the hypothesis.</td>
</tr>
</tbody>
</table>

were over 18, had had alcohol or drugs in the last 24 hours, had any color-blindness, were checked for flat-soled shoes, asked about current sickness or sickness in the last week, whether they had a history of epilepsy or any uncorrected visual/vestibular problems, and were checked for 20/25 or better visual acuity.

The methods for Experiment AIIIIE2 were similar to Experiment AIIIIE1, with the refinements described below.

For Experiment AIIIIE2, a second videotape was made, similar in all respects to the first except that a performance task was added to force attention into the CI. Two colleagues, who were separated by 180°, each held up a large sheet of poster-board. Each posterboard was white on one side and either bright green or bright red on the other. When the camera swept by, each colleague displayed the white
Table 6.5: Participant Overview for Experiment AIII E1

<table>
<thead>
<tr>
<th>Id</th>
<th>Gn</th>
<th>Age</th>
<th>Prev</th>
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</thead>
<tbody>
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<tr>
<td>107</td>
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<td>34</td>
<td>1</td>
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</tbody>
</table>

*Id* is the participant number. *Gn* gives the gender, *Age* the age in years, and *Prev* is “1” if the participant had more than 10 minutes of prior experience in virtual environments, “0” otherwise.
side approximately 75% of the time, and the colored side the other 25% of the time, with a random pattern. Participants were asked to call out the color when a colored sign appeared in the videotape. Responses were recorded on audiotape to check task performance.

Instructions to participants included the following:

You will wear a Virtual i-O HMD for this experiment. The HMD will show a rotating scene. Red and green signs will be displayed periodically; your task will be to call out “red” or “green” when you see a “red” or “green” sign. You will be asked to stand in the Sharpened Romberg stance for one minute while viewing the image. (It’s okay if you need to break the Sharpened Romberg stance; just get back into it.) You will then have one minute to relax while viewing the rotating image, followed by 1 minute more in the Sharped Romberg stance, then a minute and a half to relax while viewing the rotating image.

In addition to the three dependent measures used in Experiment AIIIIE1 (stance breaks, SSQ and reported vection), pre- and post-exposure ataxia were recorded. The pre- and post-exposure ataxia measures were made with a Chattecx Balance System (see Section 3.7.5). Postural measurements were taken with subjects in the Sharpened Romberg stance with eyes open.

The average of three trials on the Balance System prior to each condition was used as the baseline ataxia measure. The average of two trials on the Balance System after each condition was used as the post-exposure ataxia measure. (As the intent was to test for rapidly-decaying after-effects, it was not thought that more than two post-exposure readings would be useful.) Measurements were taken with participants in the Sharpened Romberg stance with eyes open. Prior to each measure, participants mounted the apparatus and were given a few seconds to attain their balance.
Participants stepped off the apparatus and stood at ease for approximately 30 seconds between trails while the results were calculated. Post-exposure measures were recorded immediately after exposure. Participants were asked to close their eyes while the HMD was removed, then open their eyes and walk directly to the Balance System, located a couple of steps away.

Exposure in each condition was for 4.5 minutes, with the first and third minutes in Sharpened Romberg. The extra 1.5 minutes at the end compared to Experiment AIIIE1 was intended to increase the chance of finding an ataxia after-effect. There was a 15 minute break between conditions, during which subjects relaxed and walked around the building to mitigate any carryover effects between conditions.

Head rolls were removed, both to reduce individual variations in how the rolls were performed and for fear that with attention forced into the spinning CI, motion sickness and ataxia might otherwise be too large.

The design of the HMD masking was improved to remove a slight breathing restriction, which might have elevated SSQ ratings over both conditions in Experiment AIIIE1.

The visibility-of-the-background rating was changed to a 1-7 scale in Experiment AIIIE2, for consistency with thevection scale and prior work.

The Balance System was also used to check that participants were back to their baseline level of postural stability before leaving the experiment.

6.3.4 Results

Sharpened Romberg data from three subjects were not analyzed due to excessive difficulty with the task, particularly in the occluded condition. However, their data were not exceptional on other variables and were therefore included in the rest of the
Table 6.6: Data From Experiment AIIIIE2

<table>
<thead>
<tr>
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<tbody>
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<td></td>
<td>See-through</td>
</tr>
<tr>
<td>SSQ</td>
<td>15.0(16.2)</td>
</tr>
<tr>
<td>Total Stance Breaks *</td>
<td>1.6(1.9)</td>
</tr>
<tr>
<td>SB1</td>
<td>0.6(0.8)</td>
</tr>
<tr>
<td>SB3</td>
<td>1.0(1.6)</td>
</tr>
<tr>
<td>Vection</td>
<td>3.0/7.0(1.7)</td>
</tr>
<tr>
<td>Background Visibility</td>
<td>2.5/7.0(0.9)</td>
</tr>
<tr>
<td>Pre-Exposure Ataxia</td>
<td>6.2(1.9)</td>
</tr>
<tr>
<td>Post-Exposure Ataxia</td>
<td>7.4(3.8)</td>
</tr>
</tbody>
</table>

“SSQ” is a reported simulator sickness value [55]. “SB1” and “SB3” are the total number of stance breaks in the first and third minute, respectively. For the skewed data (SSQ, vection and visibility ratings), medians are reported. Other values are means. Standard deviations are given in parentheses. “*” implies that the difference between conditions is significant at p < .05.

Analysis\(^2\). One outlier was removed from the visibility data (the subject rated the visual background as quite visible in both the see-through and occluded conditions). The three pre-exposure ataxia trials were averaged, as were the two post-exposure ataxia trials (after determining that the post-exposure trials were not significantly different). Data on the CI visual task (calling out the colored signs) were not formally analyzed as all subjects performed perfectly or near-perfectly in both conditions.

The data are summarized in Table 6.3.4.

Total stance breaks, and pre- and post-exposure ataxia data were normal and

\(^2\) Stance breaks are a discrete measure, and become meaningless in the case of continuous instability. The same problem does not afflict the other measures.
therefore no transformations were required. These data were analyzed with a 2-tail paired t-test. The questionnaire data, SSQ and vection ratings, were analyzed using a non-parametric, 2-tail paired Wilcoxon, as these data were markedly skewed.

Total stance breaks were significantly lower in the see-through than occluded conditions (p < .03).

No difference was found across conditions for SSQ, vection or post-exposure ataxia scores. The SSQ scores after both conditions were significantly higher than the pre-test SSQ scores (p < .03), indicating that the stimulus did have an effect, simply not a condition-specific effect. After finding no difference between conditions, pre- and post-exposure ataxia data were each pooled across conditions, resulting in significantly greater ataxia for post-exposure than pre-exposure (p < .04). This indicated the existence of increased ataxia after only a 4.5 minute exposure to a vection stimulus. Pooling across conditions, no difference was found between SB1 and SB3.

6.3.5 Discussion

Experiment AIIIIE2 found that a strong effect for reduced per-exposure ataxia remained in the presence of a CI task. This was true even though the IVB was again rated as less visible than the CI (mean rating 2.5, with 1 indicating only the CI was visible, 7 indicating only the IVB was visible). This indicates that the IVB does not have to be overpowering to be effective.

There was a sharp drop in the overall ataxia for both conditions from Experiment AIIIIE1 to Experiment AIIIIE2 (See-through: 4.1 vs. 1.6; Occluded: 9.1 vs. 2.6). We hypothesize that this was due to the absence of head rolls.

The absence of head rolls, reducing overall effects, may partially explain the lack of a significant difference on the SSQ and SB1 vs. SB3 tests (which were significantly different in Experiment AIIIIE1).
6.4 General Discussion

The findings from the experiments in this chapter suggest that IVB’s may be effective for reducing simulator sickness and simulator-induced ataxia. It is encouraging that strong effects were found in this initial work, using short exposure durations, a low-end HMD with limited FOV, and a simple manifestation of the IVB concept.

Rest frame selection appears to be a pre-conscious operation: we are not generally aware of how our perceptual system determines what will and will not be interpreted as stationary. Consequently, it may be possible to induce a visual rest frame which avoids motion sickness and simulator side-effects without impinging on attention, and thus distracting from the task at hand.

It is noteworthy that a significant decrease in total stance breaks (in both experiments) and SSQ ratings (in Experiment AIIIIE1) was possible without a significant difference in vection ratings between conditions. In the experiments, we used a post-rather than per-exposure vection measure, to avoid an additional load on participants during trials. It is possible that a more sensitive per-exposure vection measure would have found a difference between the two conditions: this is an interesting topic for future research. However, we believe that current data are sufficient to indicate that there was not a large difference in vection between the two conditions. If one accepts that vection is related to the sense of presence in a virtual environment (see Chapter 3) this suggests that an IVB can produce performance and simulator sickness benefits without substantially reducing the sense of presence in a simulator.

The significant difference between pooled pre- and post-exposure ataxia scores in Experiment AIIIIE2 is important, given that exposure durations were only 4.5 minutes per condition and only a low-end system was used. This is an indication of how easily VE’s can produce after-effects. However, these after-effects seemed to disappear quickly: no difference was found for pre-exposure ataxia between the first and second conditions, with a 15 minute break before the second condition.
Furthermore, subjects were required to perform at their baseline levels of postural stability before leaving the area. This occurred within 10 minutes after the second exposure for all subjects.

An improved use of the IVB might be to put it in the periphery of the display. In the current implementation, subjects often reported that they lost track of the visual background when focusing on the CI. Placing the IVB in the periphery might allow the IVB to be processed non-competitively and unobtrusively in peripheral vision. This is a topic for future research.
Chapter 7

GENERAL DISCUSSION

*Here about the beach I wander’d, nourishing a youth sublime*

*With the fairy tales of science, and the long result of Time.*

— Alfred Lord Tennyson, *Locksley Hall*

### 7.1 Introduction

This chapter gives a high-level discussion of the research described in the previous chapters. It follows the division into 3 areas which was introduced in Chapter 3. Suggestions for future research appear in Chapter 8.

### 7.2 Area I: Presence Measures

The following research questions were posed at the top of Chapter 4:

1. How should a rest frame conflict measure be implemented?

2. Is the presence hypothesis correct? That is, does a measure based on real-virtual rest frame conflict evaluate our subjective sense of presence?

3. What is the test-retest correlation of a rest frame conflict measure?

4. How is the rest frame conflict measure related to field dependency?

The research described in this dissertation has made significant progress towards answering these questions. A measure based on visual-inertial nulling in the horizontal
plane was introduced; in Experiment AIE2, it was used to find a main effect in agreement with prediction and with a trend in reported presence; a reasonable test-retest correlation (.83) was found; and data was collected on the correlation between the nulling measure and the Embedded Figures Test.

That said, one must point to the limitations of this research. In Table 4.7 (page 78) there is no difference between conditions on the nulling measure for 13 matched pairs out of 24\(^1\). This implies that the measure was having difficulty distinguishing the conditions. And this for a meaningful/random comparison, which one might expect to produce large differences between conditions.

This lack of sensitivity was probably due in part to equipment limitations. The resolution was set quite low (240x320 pixels) to maintain a 60 frames-per-second update rate, and the FOV, at 48°, was somewhat below what is usually considered the threshold for high presence. Both of these may have introduced floor effects.

However, the lack of interactivity inherent to the procedure used in Chapter 4 may also have played a role. An environment which does not support interactivity may not tend to “draw people in” with an intensity needed to clearly demonstrate differences between conditions. In addition to introducing a possible floor effect, the lack of interactivity limits what the procedure of Chapter 4 can be applied to. While it is suited to investigating general display factors such as the relative importance of FOV and resolution, or measuring the foreground occlusion effect, interactive virtual environments fall outside of its scope. A possible visual-inertial nulling measure suited to interactive environments, based on the “induced motion” effect found in

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\(^1\) The distribution is similar for the reported presence measure. Again from Table 4.7 (page 78), for 9 matched pairs out of 24 there is no difference between conditions, for 13 matched pairs the meaningful condition was rated higher, and in 2 the random condition was rated higher. This suggests that the frequent lack of difference in the visual-inertial nulling measure data across conditions was due to the nature of the experiment rather than to a specific lack of sensitivity for visual-inertial nulling.
Pilot Study AIIIP2 (see Appendix D), will be discussed in Chapter 8. The underlying perceptual phenomenon will be discussed below in Section 7.4.

A possible (if untested) benefit of nulling presence measures may be a reduced anchor effect (see Section 2.3.3). A cost of the anchor effect is that one can not readily make comparisons between scores on conditions which were not directly compared in the same experiment. This makes it difficult to incrementally build knowledge by a series of disjoint experiments.

As an example of the anchor effect, consider the reported presence ratings in Experiment AIE1 (Table 4.3, page 71) and Experiment AIE2 (Table 4.7, page 78). The condition labeled “48°” in Experiment AIE1 was identical to the condition labeled “Meaningful” (MRP) in Experiment AIE2. Yet the reported presence for this condition from the two experiments is quite different. Averaged across first and second reports, the value for the “48°” condition in Experiment AIE1 was 4.8, whereas the value for the “Meaningful” condition in Experiment AIE2 was 2.75. This difference is highly significant on a two-sample t-test (p < .001). The difference presumably arises because in Experiment AIE2 the comparison was against a random scene, which tended to lower over-all presence ratings. In Experiment AIE1, the comparison was against two similar conditions of slightly narrower FOV.

Anchor effects for reported presence are not surprising. Humans were not evolved to assign numbers to mental states and have no robust means for doing so. While there are currently no data on this, it may be that a nulling presence measure, being more deeply-rooted psychologically than self-reported presence values, may exhibit much more consistency across experiments.

Both Experiment AIE2 (Table 4.7, page 78) and Pilot Study AIP4 (Table B.2, page 147) found roughly a factor of 10 between-participant difference in where the cross-over amplitude occurred. Similar differences were found in Pilot Studies AIP1 and AIP2, using different equipment. A factor of 10 is a conservative estimate: participants exceeded the range of measurement in both directions. A possibility is that
the between-participant variation in the cross-over amplitude reflects a more sensitive measure of field dependency than has previously been available. Like the EFT and the rod-and-frame test, the visual-inertial nulling measure requires participants to extract a signal from a conflicting or distracting visual pattern. But the visual-inertial nulling procedure uses a more compelling visual stimulus than either of the other two tests; and, in addition, the visual-inertial nulling procedure avoids the strong gravitational cue which is present in the rod-and-frame test.

The visual-inertial nulling procedure might also be used clinically as a means to diagnose vestibular damage.

About a third of the participants in Experiment AIE1 did not follow the general pattern that the 48° condition produced higher reported presence than the other two conditions. This suggests that for a minority of the participants, the effect of a foreground occlusion increasing presence may have been stronger than the effect of wider FOV increasing presence, at least for relatively narrow FOV’s.

The protocol for Experiment AIE1 and Experiment AIE2 called for reported presence data to be gathered with the visual and inertial motions congruent, but with different sinusoidal amplitudes (30°/sec and 20°/sec, respectively). An informal observation is that participants did not seem to be aware of what the relationship was between the visual and inertial amplitudes, even to the extent of knowing whether or not they were equal. While visual-inertial phase differences are very apparent, amplitude differences are not, at least at the conscious level.

SSQ data were gathered before and after every session. These data were not formally analyzed, as they were gathered primarily to make a rough check that participants were not experiencing serious malaise. Simulator sickness did not appear to be a serious problem². The lack of strong symptoms in an experiment which involved a clear visual-inertial sensory conflict may seem surprising. It is probably due to

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² In a few cases, participants reported feeling better after the experiment than before. This may have been a beneficial side-effect of the instruction to “relax and close your eyes” between trials.
the short duration of exposures to the conflicting stimuli. Exposures tended to be about a minute long, separated by a rest with eyes closed of one or two minutes while conditions were changed. It appeared that participants exposed to conflicting stimuli for longer periods of time did develop symptoms of simulator sickness.

7.3 Area II: Presence Manipulations

The following research questions were posed at the top of Chapter 5:

1. Can a foreground occlusion increase reported presence?

2. Can a performance measure be found for the effect of a foreground occlusion?

Experiment AIIE1 and Experiment AIIE2 found the predicted effect of a foreground occlusion increasing reported presence. While this result is to be expected from the vection literature, it appeared to come as a surprise to most virtual environments researchers at the time. These experiments served the twin purposes of supporting the hypothesized link between vection and presence and of pointing out an application of foreground occlusions to HMD design.

The literature and pilot study reported in Appendix E point to another application of foreground occlusions to HMD design, besides increasing presence. Foreground occlusions may also be useful to reduce binocular rivalry for displays with a partial overlap between the scenes displayed to the two eyes.

Appendix C reports on a series of studies which sought a performance measure for foreground occlusions, in terms of a spatial orientation task. While two pilot studies were promising, the full experiment (AIIE3) failed to find an effect. Possible modifications to Experiment AIIE3 are discussed in Appendix C. However, based on current data, it appears doubtful that the foreground occlusion effect will be successfully measured with experiments similar to AIIE3.
Given the subjective strength of the foreground occlusion effect (as measured in Experiments A1IE1 and A1IE2) it would be surprising if it could only be detected by self-report measures. The search for a foreground occlusion performance measure might pursue a spatial task which more clearly requires a switch of the selected rest frame away from the laboratory and into the scene shown on the display. However, it is not immediately clear what an appropriate task would be. Alternatively, an attempt might be made to measure the foreground occlusion effect with a nulling measure.

7.4 Area III: Motion Sickness

The following research questions were posed at the top of Chapter 6:

1. Can an independent visual background (IVB) in agreement with inertial cues reduce reported simulator sickness and related side-effects?

2. If so, can it do so without reducing the subjective impact of the scene?

3. Can an IVB be effective even when attention is directed into the visual foreground, in which visual self-motion cues disagree with the inertial cues?

Experiments AIIIIE1 and AIIIIE2 answered all of these questions in the affirmative. However, these experiments dealt only with a “low-end” system based on the Virtual i-O i-glasses!. An important open problem is to investigate the usefulness of the IVB technique for high-end systems.

Pilot Study AIIIIP2 (see Appendix D) was a very brief investigation of a simple background grid as an IVB for a high-end driving simulator. It failed to find a reduction in simulator sickness. Pilot Study AIIIIP2 is reported because it serendipitously found a possible nulling presence measure suitable for interactive environments. The
possible measure will be discussed in Chapter 8. The below comments on the underlying phenomenon.

Pilot Study AIIIIP2 used a simple background grid for the IVB, displayed in the sky portion of the simulator scene. The grid was kept fixed with respect to the laboratory at all times. There was a fascinating effect in which the background grid appeared to rotate in the opposite direction when the CI turned, even though the background grid was stationary with respect to the laboratory\(^3\). This is known as “induced motion”: the apparent motion of a stimulus caused by motion of nearby stimuli (see Section 3.3.2).

While it is usually a motion of the visual background which produces an induced motion of a foreground object, the reverse is not unknown. Levine and Shefner [60] give the following example: “...consider a cloudy night sky with the moon ducking in and out of the drifting clouds. The moon is actually stationary relative to the clouds, but because the clouds take up so much more room in the visual field than the moon, they appear to be stationary while the moon seems to move in the opposite direction from them.” (p. 382.)

See Section 3.3.1 for a discussion of why this induced motion may have occurred. It seems likely that a more compelling visual background than a simple grid would serve to reduce simulator sickness. But this remains a topic for future research.

### 7.5 Selected Rest Frames and Cognition

Selected rest frames have been presented in this dissertation as a purely perceptual phenomenon, although affected by cognitive issues such as the focus of attention (see Section 3.3.1). An interesting question is to what extent selected rest frames operate

\(^3\) For myself, at least, the impression was that the CI and the background grid were mounted on independent (not visible) disks, which were free to rotate independently. The disk the background grid was on appeared to slide in the opposite direction during turns.
on principles similar to cognition.

An analogy can be drawn between the operation of the selected rest frame and of chunking. “Chunks” refer to familiar patterns stored in long-term memory. Human information processing makes heavy use of chunking. A complex pattern of information which has been chunked is often easier to process than a smaller amount of unfamiliar information. An interesting recent example of this is provided by Luck and Vogel [63], who mention that

...objects defined by a conjunction of four features can be retained in working memory just as well as single-feature objects, allowing sixteen individual features to be retained when distributed across four objects. Thus, the capacity of visual working memory must be understood in terms of integrated objects rather than individual features...

Chunks underlie memory of the environment. Chase and Simon [18] found that while expert chess players are better at remembering meaningful chess positions than are novices, the two groups perform equally poorly on random chess positions. Experts chess players (and, presumably, humans in general) remember by breaking the environment into previously-learned patterns.

The same chunking which drives both short-term and long-term memory is also active in visual perception. There are numerous visual illusions which imply that the perceptual system seeks familiar patterns (chunks), to the extent that it can be fooled when the pattern is not entirely there.

It seems likely that the nervous system does not merely look for and remember chunks: it also represents unfamiliar information in terms of its differences from known chunks. It is more efficient to view new information as “almost like such-and-such except for...” than it is to analyze new information from scratch. Viewed in this

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4 See, for instance, the discussion of “illusions dependent on perceptual hypotheses” in Levine and Shefner [60].
way, one's set of chunks do not simply define a set of isolated points: they define a coordinate system in terms of which new information can be represented\textsuperscript{5}.

This resembles the role hypothesized for the selected rest frame. The selected rest frame is hypothesized to serve as the comparator for spatial judgments. Spatial judgments are made by describing how things relate to (are different from) the selected rest frame.

This suggests that the selected rest frame can be thought of as the "underlying chunk" for spatial perception. Selected rest frames may therefore be closely related to the operation of chunking in cognition.

\textsuperscript{5}That is, new information can be thought of as being defined in terms of its projection onto known chunks, which act as basis vectors.
Chapter 8

FUTURE RESEARCH

If we knew what it was we were doing, it would not be called research, would it?

— Albert Einstein

8.1 Introduction

The preceding chapter summarized the dissertation experiments. This chapter suggests future research. It follows the division into 3 areas which was introduced in Chapter 3.

8.2 Area I: Presence Measures

8.2.1 Improved Equipment

As discussed in the previous chapter, the visual-inertial nulling measure appeared to suffer from a floor effect which may have been due in part to equipment limitations. Simply improving the equipment should make the visual-inertial nulling measure better able to detect differences between conditions. This might include faster processing to allow for higher resolution; the use of stereo images; a wider FOV HMD; and the use of (possibly spatialized) auditory cues.
8.2.2 Individual Variation

Experiment AIE2 and Pilot Study AIP4 found at least a factor of 10 between-participant variation in the cross-over amplitude. What is the source of this variation? It was suggested in the previous chapter that this variation might reflect a sensitive measurement of field dependency. A second possibility is that it reflects individual variation in the degree to which the participant attended to the visual scene. Those who watched the scene more carefully would be expected to be more influenced by the vection stimulus, which would be reflected in a higher cross-over amplitude.

The relative influence of inherent individual differences and of variation in attention level could be assessed by providing a visual task. For instance, attention level could be controlled for by having participants push a button every time a red dot appeared on the screen\(^1\).

8.2.3 A Possible Induced Motion Measure

A primary advantage of the visual-inertial nulling procedure developed in Chapter 4 is that it factors out the strong inertial cues from gravity. However, this visual-inertial nulling procedure has serious drawbacks: it requires the full attention of the participant and completely determining the visual and inertial motion. While the visual-inertial nulling measure can address display factors such as the influence of FOV, resolution, etc., it is not suited to the study of interactive virtual environments. An important question, therefore, is whether less burdensome perceptual measures are possible which preserve the advantages of the visual-inertial nulling measure.

A possibility for such a measure is suggested by Pilot Study AIIIP2 (see Appendix D). The “induced motion” phenomenon found in Pilot Study AIIIP2 was

\(^1\)It should be noted that this procedure might introduce noise into the cross-over data, since participants would be faced with a divided attention task. They would need to respond to both the inertial motion extremes and the appearance of visual targets.
discussed in Section 7.4. Briefly, a grid in the visual background of the driving simulator which was stationary with respect to the laboratory appeared to rotate in the opposite direction when the CI in the foreground turned.

An interpretation of this phenomenon is that the selected rest frame was determined more by the CI than by the background grid or by the (lack of) inertial cues. The relative motion between the CI and the background grid was therefore perceived as a motion of the background grid. According to the presence hypothesis, the degree to which the selected rest frame is determined by the CI is related to the level of presence in the CI. This suggests that a perceptual presence measure may be constructed by measuring the amount of induced motion of the background grid.

A possible technique for doing so is as follows. Give participants a dial to turn, and instruct them to adjust the dial so that the background grid appears to be stationary during turns in the simulator. The dial has the effect of introducing a counter-rotation of the background grid to balance out the induced motion. The magnitude of counter-rotation needed to make the grid appear to be stationary is the perceptual presence measure.

The dial could be mounted on a navigational device for the simulator scene (e.g., a steering wheel) where it would be easy for the participant to adjust. If the level of presence is fairly constant the dial might not require updating frequently, in which case it would require little attention from the participant.

8.2.4 Anchor Effect

See Section 7.2 for an example of an anchor effect in the reported presence data from the current research, and a discussion of why the anchor effect limits the combination of data across experiments. It was suggested in that discussion that visual-inertial nulling measures might be less prone to the anchor effect, as they are based on a more direct measure of spatial perception.

The hypothesis that nulling measures (such as the visual-inertial nulling measure
introduced in Chapter 4) might be less prone to the anchor effect is easily testable. This could be done by a series of experiments in which the same condition “A” is compared to quite different conditions. For instance, Experiment 1 might compare condition “A” to condition “B”, Experiment 2 might compare condition “A” to condition “C”, etc. The consistency of the values obtained for condition “A” could then be compared across experiments. A comparison should be made between the consistency of a nulling measure and a self-report measure for presence.

8.2.5 Application to Interface Issues

The above subsections have suggested various ways to evaluate or improve the visual-inertial nulling measure. In the end, however, measures exist to be used. A nulling measure can and should be applied to systematically evaluate the influence of many factors, such as FOV, foreground occlusions, resolution, auditory cues, interactivity, etc.

8.3 Area II: Presence Manipulations

As discussed in Section 7.3, foreground occlusions may be useful additions to HMD’s both to increase presence at a constant FOV and to reduce binocular rivalry effects. This is an option which HMD manufacturers might want to consider more seriously. There are ergonomic and safety issues associated with using a foreground occlusion which would have to be evaluated for each HMD design.

The research of Appendix C failed to find a performance effect for foreground occlusions in terms of a simple spatial orientation task. However, a foreground occlusion effect might be measurable with a nulling measure. The relative effect on presence of a foreground occlusion and wider FOV would be an interesting topic of study. The results of Experiment AIE1 suggest that for about a third of participants, the foreground occlusion effect had as strong or stronger an effect on presence as wider
FOV, at least using a reported presence measure over a range of fairly narrow FOV’s.

8.4 Area III: Motion Sickness

Experiments AIIIIE1 and AIIIIE2 suggested that an IVB can reduce simulator side-effects even when attention is forced into the simulator scene. However, these experiments were conducted using a “low-end” system. The most important potential application of the IVB idea would be to “high-end” systems involving wide FOV displays and interactivity.

To what degree an IVB might be useful for such systems, and how it should be implemented, are open questions. Specific questions include the following.

1. What should the properties of the IVB be?

2. What is the effect of the IVB on task-performance?

The first question raises IVB design issues such as: what should the FOV, brightness, scene content, etc., be; does it need to be in central vision or can it be confined to the periphery where it would provide less of a distraction; should it be user-adjustable, and if so, which parameters should vary; which depth cues should be used to cause the IVB to be perceived to be behind the CI; should the CI/IVB mixing be done optically or in software?

The second question asks what an IVB costs. It is clear that, in the limit at least, the IVB technique can reduce simulator side-effects. In the limit, a strong IVB simply washes out the CI, avoiding simulator side-effects at the cost of rendering the simulator useless. The question, therefore, is to what degree an IVB can reduce simulator side-effects without degrading task performance. (It is also possible that an IVB may improve task performance, to the extent that it reduces malaise.)
Chapter 9

CONCLUSION

A set o’ dull, conceited hashes
Confuse their brains with college classes,
They gang in stirks and come out asses,
Plain truth to speak;...

— Robert Burns, Epistle to J. Lapraik

9.1 Overview

This dissertation sought to address key problems facing the human factors of virtual interfaces in a unified way. To this end, the RFC was introduced as a convenient summary of a considerable part of the literature on spatial perception. The RFC was applied to the problems of understanding, measuring, and manipulating presence, and to the alleviation of simulator sickness.

Presence correlates with high-level aspects of the quality of a virtual interface, including its intuitiveness and its ability to convey meaning. Therefore, a robust presence measure supports the systematic development of knowledge about how to construct virtual interfaces. This dissertation introduced a presence measure based on spatial perception, possibly at the brain-stem level. By evaluating presence at such a fundamental level the problems associated with self-report measures, such as range and anchor effects, may be reduced or eliminated.

Simulator sickness poses a critical problem for virtual interfaces. As virtual interfaces become more compelling, they become more able to cause unwanted side-effects.
To address this problem, a link through the RFC between the spatial perception literature and the motion sickness literature was exploited. This link was used to suggest a technique for reducing simulator sickness through manipulations to the visual background.

This dissertation is, of course, no more than a beginning. It does not reach closure; it seeks to steer research in particular directions. It is based on the belief that fundamental problems should be approached from fundamental principles; in this case, fundamental principles of spatial perception.

There are many interesting ways in which this research could be further pursued. These have been summarized in the preceding two chapters. The most pressing are improvements to the presence measure; its use for the systematic study of the factors affecting presence in virtual environments; and the application of independent visual backgrounds to reducing simulator sickness in high-end virtual environments. Beyond this basic research lies the application of the more sophisticated virtual interfaces which it will engender. In many application domains, well-designed virtual interfaces provide a means to confront the complexity explosion by increasing the human-computer bandwidth. But these are stories which remain to be told.
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Appendix A

**COGE1: THE INFLUENCE OF MEANING ON PRESENCE**

See Section 2.2 for a review of presence. Experiment CogE1 addressed the importance of presence, by showing that (in addition to many other factors related to the quality of an interface) presence is linked to the meaningfulness of stimuli. This adds importance to the search for robust presence measures described in Chapter 4.

This research was led by Dr. Hoffinan. As I was second author on this experiment, and as its role (for current purposes) is only supportive to research in Areas I, II and III, full details are deferred to a journal article, in press [41].

**Title:** CogE1: Cognitive Influences on Presence. **Background:** While presence is characteristic of virtual environments, the factors influencing it, and its consequences, remain unclear. Previous research has focused primarily on the computer side of the human-computer interface: *i.e.*, display issues such as FOV and lag. The current experiment studied the human side of the interface. We studied the effect of meaningfulness on presence and recall. To the extent that presence can be demonstrated to be a cognitive phenomenon, it becomes more important to study, because of the higher probability that presence will be linked to such things as performance and training transfer. **Hypothesis:** Increasing the level of meaningfulness while other variables are held constant increases the level of presence. Higher levels of expertise may correlate with a stronger effect for meaningfulness on both presence and memory performance. **Methods:** Meaningfulness was manipulated by comparing master chess positions with matched random positions. Positions were shown in
a Division dVisor HMD. Positions were labelled meaningful or meaningless in the virtual environment for the benefit of the non-players used as controls, and to thus match any possible demand characteristics between chess players and non-players. Four levels of chess expertise were used, ranging from those not knowing the rules of chess to strong tournament players. The "old-new" memory recognition task measured accuracy in reporting which positions had been seen previously. The experiment was performed double-blind, with the experimenter blind to both the hypothesis and the chess strength of particular subjects. Thirty-three unpaid adult volunteers participated. Results: Presence ratings were significantly higher for meaningful than meaningless positions for all participants except non-players. No difference in presence ratings was found between the three levels of expertise above non-players. On the old-new memory recognition task, recognition rates were significantly higher (and near-perfect) for the meaningful positions, but only for the strongest group of chess players. The meaningful/meaningless interaction with expertise was significant. Conclusions: The results show that the amount of presence felt by individuals depends on whether the contents were meaningful to them, independent of display parameters. This demonstrates that presence is related to cognitive, not simply perceptual issues. Only a small level of expertise was needed to produce a large effect of meaning on presence. The memory recall results are consistent with Chase and Simon [18], extended to a different memory task.
Appendix B

AREA I PILOT STUDIES: VISUAL-INERTIAL NULLING PRESENCE MEASURES

B.1 Initial Pilot Studies

This section describes the first two pilot studies conducted on the use of visual-inertial nulling as a possible presence measure. Different equipment was used in these studies than in those described in Chapter 4, or in the next section. Pilot Studies AIP1 and AIP2 made use of a Division ProVision 100 and dVisor HMD to provide images generated in real-time and synchronized to the chair motion. This approach led to synchronization problems and a low frame rate. The procedure of Chapter 4, which made use of a very large, precomputed image, was introduced as an improvement.

Title: AIP1: Wide Field-of-View. Background: See Section 3.3.3 for a general introduction to the use of rest frame conflict as a presence measure. The current study was an initial investigation of the following questions: 1. can a perceptual presence measure be based on rest frame conflict?; and 2. if so, is the measure closely related to reported presence, as implied by the presence hypothesis? A visual-inertial self-motion conflict was investigated. Pilot Study AIP1 explored whether the amplitude of inertial motion (from the external environment) needed to overwhelm conflicting visual motion cues (from the virtual environment) could be used as a presence measure. To avoid the strong inertial cue provided by gravity, the visual-inertial conflict was restricted to the horizontal plane. Hypothesis: Within subjects, comparing two FOV’s (40° and 105°) in an HMD, the FOV with the higher reported presence
will correlate with the FOV with the higher inertial amplitude needed to perceptually overwhelm conflicting visual self-motion cues from an HMD. **Methods:** There were 10 unpaid adult participants (7 male, 3 female). None were familiar with the hypothesis. Participants were seated in a chair which oscillated at .1 Hz in yaw (the horizontal plane). They wore a Division dVisor HMD which displayed a scene of a kitchen which also oscillated in yaw at .1 Hz. The virtual environment was generated in real-time by a Division ProVision 100, and ran at about 10 frames-per-second. Head-tracking was disabled, so that visual position updates occurred only as a consequence of the programmed sinusoidal oscillations, not due to user actions. The FOV was restricted by placing a circular black occlusion in the virtual scene in front of the virtual eye position. The phase angle between the inertial and visual was set to create a conflict between the inertial and visual self-motion cues. Participants were asked to attend to the visual scene but signal the perceived right/left inertial extremes of their motion with a slider potentiometer. A counting procedure was used as a distractor before each trial to prevent participants from “locking in” to the inertial motion. The inertial amplitude was varied following a PEST procedure to discover the “cross-over” inertial amplitude at which participants switched from correctly indicating the inertial motion of the chair (inertial dominance) to inadvertently signaling the visual motion (visual dominance). To control for learning effects, the two conditions were run in parallel, alternating on an ABBA pattern. As this was an exploratory pilot study, the magnitude and schedule of phase angles was varied across subjects, although they were matched across conditions for each subject. Subsequent to the visual-inertial nulling experiment, reported presence in the two conditions was assessed with a questionnaire (see Section 3.8.1). **Results:** Even with the rather crude virtual environment used, it was found that it was not difficult to get participants into visual dominance. The mean cross-over amplitude across conditions and subjects was an order of magnitude above the inertial detection threshold in the dark. For four of the participants, there was a factor of two or more difference between the
cross-over values between the two conditions. However, reported presence differences between conditions did not differ much between conditions, and differences were not in clear agreement with the nulling data, even for participants with the largest differences between conditions on the visual-inertial nulling measure. **Conclusions:** This pilot study established that large visual dominance effects can be created in the horizontal plane. That large effects were found between conditions on the cross-over experiment was quite encouraging for this sort of measure. However, the lack of consistency between the visual-inertial nulling and reported presence measures left open the question of whether the two measures are recording fundamentally the same psychological phenomenon, as predicted by the presence hypothesis.

**Title:** AIP2: Orientation. **Background:** Pilot Study AIP1 demonstrated that visual dominance could be easily achieved in a horizontal oscillation experiment using standard VE equipment, and that large differences between conditions could be measured. However, differences in reported presence were small and not consistent with the nulling data. This is a challenge to the presence hypothesis. One possibility was that the nulling measure was more sensitive than reported presence in AIP1. Perhaps perceptual differences existed which were not strong enough to reach the conscious level accessible to the reported presence measure. If so, the lack of correlation between the two measures might reflect noise in the reported presence measure. This hypothesis could be tested by strengthening the reported presence signal. Given the result of Experiment Cog1 (see Appendix A), a reasonable try for a strong presence difference was to compare a meaningful to a meaningless stimulus. Another possible criticism of AIP1 is that the cross-over data did not reflect a difference in presence between conditions, but rather a low-level perceptual factor: total area of retinal stimulation. To control for this, it was desirable to compare a “meaningful” to a “meaningless” visual condition which were as alike as possible in low-level perceptual issues. A candidate manipulation, easily implemented with the available software, was to compare the kitchen used in AIP1 in upright (“meaningful”) and upside-
down ("meaningless") configurations. **Hypothesis:** The upright condition should produce both higher inertial cross-over and higher reported presence scores than the upside-down condition. **Methods:** As in AIP1, with the exception of the different conditions. There were 10 unpaid adult participants (4 male, 6 female), all naive to the experimental hypothesis. None had participated in AIP1. **Results:** Unlike AIP1, no large differences were found between conditions on the nulling measure. Nor were large differences found on the reported presence measure. Nor was there a clear relationship within subjects across the two measures. **Conclusions:** The lack of a clear difference between the conditions on either measure suggest that upside-down is not the same as meaningless. The same information is present: it is simply harder to interpret. For some, the difficulty of interpreting the upside-down scene decreased reported presence somewhat; for others, the added attention required interpret the upside-down scene increased presence. But the effects (on both measures) appear to be small.

### B.2 Pilot Studies Related to Experiment AIE1

The below pilot studies examined the same conditions as Experiment AIE1, but with a nulling measure rather than reported presence. See Chapter 4 for a description of the conditions and general methods. The primary result of these pilot studies was to establish the techniques used in Experiment AIE2.

**Title:** AIP3: Narrow Field-of-View (Nulling Measure I). **Background:** This experiment applied the visual-inertial nulling measure to the same conditions as Experiment AIE1. **Hypothesis:** The nulling measure should have good test-retest correlation. Within subjects, cross-over data should be consistent with reported presence data across conditions, with higher cross-over values corresponding to higher reported presence values. Across subjects, the average cross-over value should correlate with EFT scores. **Methods:** For general methods, see Section 4.2. There were 6 unpaid
adult participants (4 male, 2 female) selected from participants in Experiment AIE1 (numbered 3, 8, 9, 14, 15 and 16 in Table 4.2). All but one were naive to the hypothesis. In each of three sessions, participants were exposed to two of the three conditions from Experiment AIE1 in alternate trials, seeing each condition twice over the course of the three sessions. A visual-inertial perceived self-motion conflict was created by randomly picking either a (±90°) phase difference between the vection and inertial stimulus for each trial. Two phase angles were used to reduce possible learning effects. An EFT was administered following one of the three sessions. Results: See Table B.1. Test-retest consistency for the cross-over data was poor (.38 correlation). In view of this low correlation, indicating unreliable results, other data were not formally analyzed. Conclusions: The lack of test-retest consistency for the nulling measure as implemented in AIP3 renders it useless. In examining the pattern of responses, it appeared that there might be a systematic difference in the difficulty of inertial tracking as a function of which of the two phase angles was used (±90°). Pilot Study AIP4 was therefore conducted with a single phase angle.

Title: AIP4: Narrow Field-of-View (Nulling Measure II). Background: An examination of the cross-over data from AIP3 suggested that the inconsistency of test-retest scores might be accounted for by a systematic difference in the difficulty of inertial tracking between the two vection-inertial phase angles used. Accordingly, AIP4 was repeated using only a single phase angle throughout. This raised the possible problem that participants would “figure out” the relation between the visual and inertial curves, consciously or unconsciously, resulting in the task becoming progressively easier over time. Hypothesis: As with AIP3. Methods: As with AIP3, except that only a single vection-inertial phase angle (90°) was used. There were 4 unpaid participants (3 male, 1 female) selected from participants in Experiment AIE1 (numbered 17, 18, 19 and 20 in Table 4.2). Results: See Table B.2. The test-retest correlation for the cross-over data was .99. Retest cross-over amplitudes were not lower than initial cross-over amplitudes, and all four participants reported believing
### Table B.1: Cross-Over Data for Experiment AIP3

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<tr>
<td></td>
<td>9.7(7.5)</td>
<td>10.1(6.9)</td>
<td>10.1(3.9)</td>
<td>11.8(4.9)</td>
<td>10.4(8.3)</td>
<td>13.4(9.7)</td>
<td></td>
</tr>
</tbody>
</table>

*Id* is the participant number (consistent with the numbers in Experiment AIE1). The next 6 columns give the first and second cross-over amplitudes (in $^\circ$/sec) for the $16^\circ$, $32^\circ$, and $48^\circ$ FOV conditions, respectively. (These data are the mean of cross-over ranges, as described in Section 4.2.) Higher values indicate more visual capture. The last column gives Embedded Figures Test scores. The final row gives the mean and (in parentheses) standard deviation for each column.
Table B.2: Cross-Over Data for Experiment AIP4

<table>
<thead>
<tr>
<th>Id</th>
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<th>16° (2)</th>
<th>32° (1)</th>
<th>32° (2)</th>
<th>48° (1)</th>
<th>48° (2)</th>
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<td>4</td>
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<td>3</td>
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</tr>
<tr>
<td></td>
<td>8.25(12.8)</td>
<td>10.6(13.0)</td>
<td>11.8(12.4)</td>
<td>10.6(13.0)</td>
<td>11.5(12.6)</td>
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<td></td>
</tr>
</tbody>
</table>

*Id* is the participant number (consistent with the numbers in Experiment AIE1). The next 6 columns give the first and second cross-over amplitudes (in °/sec) for the 16°, 32°, and 48° FOV conditions, respectively. (These data are the mean of cross-over ranges, as described in Section 4.2, except where an upper bound was not found. In these cases, the lower bound of 30°/sec was used.) Higher values indicate more visual capture. The last column gives Embedded Figures Test scores. The final row gives the mean and (in parentheses) standard deviation for each column.

(incorrectly) that the phase angle varied across trials. This suggests that a learning effect related to using a single phase angle was not a significant factor. While the mean cross-over amplitude was lower for the narrowest FOV than for the other two conditions, the difference was too small to be significant with available data. There was a between-subjects difference in cross-over amplitudes of at least a factor of ten, with no comparable difference in the reported presence data from Experiment AIE1.

**Conclusions:** A single phase angle (90°) protocol is workable, and clearly superior to a protocol with both ±90° phase angles. The test-retest correlation of .99 was unexpectedly high, and probably related to the small sample size.
Appendix C

AREA II PILOT STUDIES: FOREGROUND OCCLUSIONS

C.1 Foreground Occlusions Increase Presence

For a more complete description of Pilot Study AIIP1, see Prothero and Hoffman [82].

Title: AIIP1: Foreground Occlusions and Field-of-View. Background: A theoretical argument based on selected rest frames put forward in this dissertation suggests that foreground occlusions (as well as FOV) should influence presence. How are the two manipulations related? If presence depends heavily on whether the display contents are interpreted as being the visual background, it might be that FOV is irrelevant if a foreground occlusion is used to block out depth cues at the same or greater distance than the display contents. Hypothesis: If a foreground occlusion is installed, presence does not depend on FOV. Methods: Thirty-eight participants were exposed to the interactive “Sharkworld” environment on a Division ProVision 100 using a dVisor HMD. Exposures were for 2.5 minutes in each of two conditions. In one condition, the FOV was an unrestricted 105°, with no foreground occlusion. In the other condition, the FOV was restricted with a foreground occlusion to 40° (which could be fo viated on) or equivalently 60° (which could be seen with peripheral vision). The order of conditions was counter-balanced across subjects. After the experiment, a written questionnaire was used to measure reported presence in the two conditions. Results: Presence ratings were analyzed with a non-parametric Wilcoxon signed-rank test. Presence ratings were significantly lower in the foreground occlusion than
the full FOV condition \((Z = -2.4, p = 0.02)\). **Conclusions:** FOV apparently has a positive effect on level of reported presence even when a foreground occlusion is used. For this reason, FOV was controlled for in subsequent experiments examining the effect of foreground occlusions (AIIE1, AIIE2, AIIP2, AIIP3 and AIIE3).

### C.2 Inside-Out Display Pilot Studies

**Title:** AIIP2: Inside-Out Displays and Optical Flow. **Background:** A sensitive measure for control-reversals would be useful as a means to investigate the possible relationship between presence and selected rest frames, and to measure the effect of particular manipulations on presence. AIIP2 examined the sensitivity of a particular control-reversal measure by testing its ability to detect the influence of a manipulation known to affect control reversals (the use or absence of moving textures on the ground representation of an inside-out display). **Hypothesis:** Either accuracy or reaction-time (RT) or both should be improved on an inside-out display roll-correction task when a moving texture is present on the ground representation. **Methods:** Twenty-two adults volunteered, none familiar with the hypothesis. The task consisted of correcting an inside-out depiction of an aircraft roll on a computer monitor by pressing either the left or right arrow key. Accuracy and RT were measured. The independent variables were presence/absence of a moving texture of the ground portion of the display; roll angle; and pitch angle. The roll/pitch combinations used were \(\pm 60^\circ/-20^\circ, \pm 100^\circ/-20^\circ, \pm 130^\circ/-10^\circ\) and \(\pm 160^\circ/-10^\circ\). There were two replications of each roll/pitch combination for each condition, for a total of \(2^2\times 2 = 32\) trials per participant. There was a block on moving vs. static ground representations. (The block was to allow for a “build-up of effect” in the moving condition.) Order of angle combinations were randomized within each block. RT-accuracy studies have a data analysis problem if the two dependent measures vary in opposite ways across conditions. In AIIP2, accuracy was controlled for by only analyzing RT’s for par-
participants who picked the correct roll at least 14/16 times in both conditions. This was consistent with preliminary data suggesting that this accuracy level would generally be met, and with the expectation that any significance would be in the RT data, rather than in accuracy. To maintain counter-balancing across condition orders at the required accuracy threshold, successive participants were added as needed to either order. **Results:** In the condition order with the moving texture ground representation first, 8/8 participants met the accuracy threshold. In the condition order with the static representation first, only 7/14 participants did so. This difference is significant on Fisher’s exact test (p < .02). For those above the accuracy threshold, there was a strong order effect for accuracy (p < .003) and a trend towards an order effect for reaction-times (p < .07) with the second condition performing better in each case. There was no difference on a paired t-test of median RT’s between conditions for those above the accuracy threshold. On questionnaire data, 11 participants reported believing they performed better with the moving texture; 5 indicated no preference; and 6 stated that the moving texture was a counter-productive distractor. **Conclusions:** The difference in accuracy-threshold between the two condition orders, together with the strong order effect, imply that the static condition was measurably more difficult that the moving texture condition. This suggested that a control-reversal measure might be viable, with refinements to reduce the strong order effect, which may obscure differences between conditions.

**Title:** AIIP3: Inside-Out Displays and Foreground Occlusions I. **Background:** AIIP2 implied that the control-reversal measure could distinguish between moving-texture and static ground conditions. This study applied the measure to another pair of conditions: foreground occlusion/no foreground occlusion. Modifications were made to attempt to reduce the order effect found in AIIP1. **Hypothesis:** The use of a foreground occlusion, by making the inside-out display the visual background, should increase the likelihood that the ground representation of the inside-out display will define the selected rest frame. This should improve performance on a roll-correction
task. **Methods:** Similar to AIIP2. Three adult volunteers, all male. One was familiar with (but did not believe) the hypothesis. The images of a plane and of a ground representation with a moving texture were displayed on a computer monitor. The images were in a circle, surrounded by a black annulus which covered the rest of the monitor. In front of the monitor was mounted an adjustable camera iris at eye level, surrounded by black tarp to remove peripheral cues. The diameter of the iris was adjustable. In the foreground occlusion condition, the inner edge of the black annulus was obscured by the foreground occlusion. In the non-foreground occlusion condition, the FOV was expanded so that one could see part of the black annulus. The monitor was viewed from a distance of about 22 cm. The FOV of the scene was about 30°. In the foreground occlusion condition, the FOV was set at about 27°. In the non-foreground occlusion condition, the FOV was about 45°, with the outside 15° showing the black annulus. Several modifications were made to make the task more difficult than in AIIP2, to reduce the order effect. The first modification was to allow both the ground and the plane to roll, with the task being to find the shortest direction (left or right) to align the plane with the ground. The second modification was to increase the number of possible angles, selecting randomly with replacement from the set of plane rotation angles \( \pm (55°, 65°, 75°, 85°, 95°, 105°, 115°, 125°, 135°, 145°, 155°) \); from the set of ground rotation angles \( \pm (60°, 70°, 80°, 90°, 100°, 110°, 120°, 130°, 140°, 150°, 160°) \); and from the set of pitch angles

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1 For those interested in replicating AIIP3 or AIIE3, I should emphasize the importance of not providing useful reference frame cues surrounding the display in the non-foreground occlusion condition. In preliminary studies, not reported in this dissertation, the aircraft icon was kept fixed and the wide FOV condition allowed spatial orientation cues from the laboratory. These studies found a strong effect against the foreground occlusion condition. A possible interpretation, suggested by Dr. Parker, is that one needs to know two orientations to solve the inside-out roll correction problem: the angle of the ground and the angle of the plane. The spatial cues from the laboratory were in agreement with the aircraft icon, which made the orientation of the aircraft icon easier to interpret, which improved performance in the non-foreground occlusion condition.
±(0°, 10°, 20°). The third modification was that a longitudinal design was used with 8 blocks of 16 trials in each of the foreground occlusion and non-foreground occlusion conditions. Each participant had 2 sessions of 4 blocks each, conducted on separate days. The condition blocks followed an ABBA pattern, counter-balanced across participants. **Results:** Examining adjacent pairs of trial blocks with a paired two-tail t-test on error rate and RT, the error rate was significantly lower in the foreground occlusion condition. (Foreground occlusion: median = 1.2/16, STD = 1.5/16; non-foreground occlusion: median = 1.8/16, STD = 1.5; p < .04). There was no difference in RT’s. **Conclusions:** The finding that there was a significant difference in errors, but not reaction-times, was consistent with AIIP2. A possible interpretation is that participants thought of the two conditions as being identical, and therefore responded at the same rate. The difference between the two conditions therefore showed up in the error rate. This interpretation is consistent with the fact that none of the participants reported feeling a difference in their performance between conditions.

**Title:** AIE3: Inside-Out Displays and Foreground Occlusions II. **Background:** AIIP3 found an effect of foreground occlusion to reduce the error rate for a roll-correction task. However, this was based on a longitudinal study of only 3 participants. AIE3 sought to replicate this result with a larger sample size. **Hypothesis:** The use of a foreground occlusion, by making the inside-out display the visual background, should increase the likelihood that the ground representation of the inside-out display will define the selected rest frame. This should improve performance on a roll-correction task. **Methods:** Nine adults volunteered (6 male, 3 female). None were familiar with the hypothesis. The procedure was identical to AIIP3, except that a study of the error distribution from AIIP3 was used to bias the trials towards the most difficult cases. (This was done with the intent to increase the low error rate from AIIP3, and thus to allow a difference between the conditions to show more clearly.) In AIIP3, The trials in which plane and ground had opposite rolls produced 80% of
the errors. There were twice as many errors in pitch up as pitch down conditions (see Figure C.1). To try to increase the error rate, therefore, the random selection of angles was biased 80% towards opposing rolls, and 80% towards pitch $\geq 0^\circ$. As in AIIP3, participants were run through 16 blocks of 16 trials. As there were 9 participants in AIIIE3, the below results summarize $9 \times 16 \times 16 = 2304$ trials. **Results:** Examining adjacent pairs of trial blocks with a paired two-tail t-test on error rate and RT, no significant difference was found between the foreground occlusion and non-foreground occlusion conditions on either error rate (Foreground occlusion: median = 1.6, STD = 2.0; non-foreground occlusion: mean = 1.7, STD = 2.4) or on median RT in seconds (Foreground occlusion: median = .29, STD = .18; non-foreground occlusion: median = .28, STD = .18). The possibility was considered that an effect existed in the early blocks which was obscured by a performance asymptote in later blocks. However, no difference between conditions was found in the first 8 blocks, nor in the first 4 blocks. **Conclusions:** It is noteworthy that the angle selection procedure described above did not succeed in increasing the error rate from AIIP3 to AIIIE3. This suggests that the task is overly simple, and that a performance asymptote is quickly reached. If so, a better approach than used here might be to alternate trials with and without the foreground occlusion, rather than taking blocks of 16 trials in each condition. This was not done in AIIIE3 for two reasons: the difficulty of quickly re-adjusting the apparatus, and to allow for a “build-up of effect” within each condition block. A further try (using the inside-out display metaphor) would be to use participants with no training on inside-out displays and record their intuitive response for correcting a roll as a function of the presence or absence of a foreground occlusion. One would hypothesize (if foreground occlusions do affect the selected rest frame) that there would be a stronger tendency to mis-interpret inside-out displays in the absence of a foreground occlusion.
Pitch Down

Pitch Up

Pitch Level

Figure C.1: Inside-Out Display Pitch Representations
Appendix D

AREA III PILOT STUDIES: MOTION SICKNESS

Title: AIIIP1: Undisturbed Postural Stability. Background: Experiment AIIIE1 found an increase in ataxia (measured in terms of stance breaks from the Sharpened Romberg position) from the first to the third minute when exposed to a circularvection stimulus. The current pilot study measured the background level of stance breaks without the vection stimulus. Hypothesis: In the absence of a vection stimulus, few stance breaks occur under the protocol of Experiment AIIIE1. Nor do the number of stance breaks increase significantly over a period of 3 minutes. Methods: Eight participants were asked to follow the protocol of Experiment AIIIE1 for one 3-minute session, while wearing the Virtual i-O HMD but without being exposed to moving visual stimuli. Five of these participants had their eyes open, simulating the see-through condition. Three had their eyes closed, simulating the occluded condition. Results: Seven of the 8 had no stance breaks at all. The 8th, with eyes closed, had 3 stance breaks in the first minute and 1 in the third minute. Conclusions: The stance breaks found in Experiment AIIIE1 were due to the vection stimulus. The increase in stance breaks from the first to third minutes in Experiment AIIIE1 was due to a build-up of effect, rather than to fatigue.

Title: AIIIP2: Independent Visual Background III (high-end). Background: Experiments AIIIE1 and AIIIE2 report initial findings that an IVB can be useful for reducing simulator side-effects for low-end systems. The current pilot study investigated whether the same is true for a high-end driving simulator, in which the nauseogenic stimulus is much stronger. Hypothesis: Providing an IVB consistent with the inertial rest frame may reduce simulator side-effects, even when the simula-
tor’s content-of-interest (CI) is not consistent with the inertial rest frame. **Methods:** Eight subjects drove figure-eights in the Hughes Research Laboratories driving simulator\(^1\) for 10 minutes at simulated speeds of 15-30 miles-per-hour. Inertial cues were not used. In separate conditions, a gray grid with about 2° spacing was either not present, appeared as an independent visual background (only in the sky, with elements from the simulator scene sweeping over and occluding the grid during turns) or (since it was an easy manipulation to try) in the foreground, as a mesh overlaying the entire simulator scene. In all cases, the grid was stationary with respect to the laboratory. The experimental design was between subjects, to avoid demand characteristics. Simulator sickness questionnaire [55] and ataxia data were recorded. **Results:** The research time available was too short to reach definitive conclusions. Informal observations included the following: 1. The background grid did not appear to reduce simulator sickness. 2. The background grid was often perceived as counter-rotating in the opposite direction during turns, despite the fact that the background grid was stationary with respect to the laboratory. 3. A foreground grid did appear to be somewhat effective in reducing reported simulator sickness, perhaps by breaking up the scene and thus reducing its believability. **Conclusions:** The “induced motion” of the background grid suggests that the selected rest frame was determined by the CI, not the IVB. In accordance with the presence hypothesis (Section 3.3.3), measuring the amount of induced motion of the background grid may provide a useful perceptual measure for the degree of presence in the CI. Unlike the “cross-over” measure of Chapter 4, the “induced motion” measure is potentially suitable for interactive environments. Further, the “induce motion” measure may provide only a minimal extra load on the participant. See Chapter 8 for a discussion.

\(^1\) See Section 3.7.2 for a description of the simulator.
Appendix E

FOREGROUND OCCLUSIONS AND BINOCULAR RIVALRY

The below literature review and pilot study is labelled “BRP1” in Section 3.5.

This section differs from the rest of the dissertation in that it is not directly related to presence or to the RFC. It is included because of its practical importance, and because it points to another important use for foreground occlusions in HMD’s, besides increasing the sense of presence (see Section 3.3.4 and Chapter 5)\(^1\). The discussion is primarily based on research by others and on theoretical arguments. Only informal new data is presented here.

HMD’s typically provide a separate screen for each eye. In the simplest case, there is a total overlap between the images presented in the two screens. That is, each screen shows the same scene, although from a slightly different angle corresponding to the distance between the two eyes.

However, there is a strong temptation in HMD design to only partially overlap the images from the two eyes. In this configuration, only the central 40° or so of the FOV is shared between the two displays. Outside of this region, each eye sees a peripheral region which the other eye can not see.

The advantage of partial overlap is that it allows a wider FOV to be seen with the same equipment. Furthermore, since binocular vision is only effective in the central region where both eyes can converge easily, there should in principle be little

\(^1\)The application described here of foreground occlusions to the binocular rivalry problem was suggested by Furness (personal communication).
perceptual cost to partial overlap.

The disadvantage of partial overlap is an unfortunate binocular rivalry effect [66, 56, 35]. The shared binocular region is flanked on both sides by monocular regions. At each boundary between the monocular and binocular regions, one eye sees the nasal (inner) edge of a screen, and the other eye sees the monocular continuation of the scene. Thus, the two eyes provide different information about the same point in the visual field.

This presents the brain with a conflict: what is “really” out there? The edge of a screen (as indicated by one eye) or the scene displayed to the other eye? The conflict tends to be resolved in favor of the edge of the screen. One perceives two dark bands, corresponding to the nasal edge of each screen, in the shared visual field. When the boundaries of the screen are circular this effect is known as “luning”.

Why is the conflict resolved in favor of the edge of the screen? Why does one not instead perceive a continuous scene, with the display edges suppressed? This question is usually addressed in terms of contrast gradients. Levelt [59], for instance, did an extensive and quantitative study of binocular rivalry. In general, if conflicting images are presented to the two eyes, the one with the higher contrast gradient is the one perceived (weighted, to some degree, by eye dominance). In the case of an HMD, the edge of the screen is usually dark black, whereas the screen itself is brightly illuminated. This creates a very strong contrast, which perceptually dominates the continuous scene viewed in the other eye. Consequently, the edge of the scene is perceived, resulting in the luning effect.

A method to ameliorate the luning effect is therefore to reduce the contrast gradient at the edge of a screen. Haseltine [35] recommends accomplishing this by placing an aperture stop near the front surface of each eyepiece of an HMD so that the binocular boundaries of the left and right fields of view are substantially out of focus. The aperture stop is out of focus, and
thus relatively inconspicuous, because the observer is focusing on distant virtual images, and also because the aperture stop may be closer to the eye than the shortest distance at which the eye is able to focus.

Lighting the boundary of the screen, so that the screen fades off slowly into blackness, might also be considered.

It is certainly true that contrast gradients play a role in binocular rivalry, and hence that reducing contrast gradients at the edge of the screen should reduce the lumining effect. However, a different approach to the lumining problem is suggested by thinking of binocular rivalry as a high-level phenomenon, associated with competing perceptual interpretations, rather than as a low-level phenomenon associated with competing monocular stimuli.

Logothetis et al. [61] mention that “binocular rivalry is thought to reflect competition between monocular neurons within the primary visual cortex. However, neurons whose activity correlates with perception during rivalry are found mainly in higher cortical areas, and respond to input from both eyes. Thus rivalry may involve competition between alternative perceptual interpretations at a higher level of analysis.” They describe an experiment in which alternating images compete independently of the eye from which they are detected.

Similarly, Shimojo and Nakayama [95] note that real world occlusions result in unpaired regions: the corresponding parts of the two eyes receive different images in the region of the occlusion. “The authors report a demonstration and experiments to show that opto-geometrically ‘valid’ unpaired regions are seen as continuous with the rear plane and escape interocular suppression, whereas ‘invalid’ unpaired regions are perceived as closer and are suppressed vigorously. An additional experiment indicates that the results cannot be understood in terms of correspondence solving, but require neural mechanisms that embody real-world occlusion constraints.”

These observations suggest that the lumining effect does not arise from conflicting
binocular cues per se, but rather from conflicting perceptual interpretations. (This bears a resemblance to the interpretation of motion sickness put forward in Section 3.3.5.) From this point-of-view, the fundamental problem is not that there is a sharp contrast at the nasal screen boundary which does not correspond to the scene in the other eye. The problem is that the perceptual system can not find a consistent interpretation of these disparate stimuli.

One might summarize the problem as follows.

1. Inconsistent images are provided to paired regions of the two eyes. (Screen boundary in one eye, visual scene in the other.)

2. The perceptual system has no consistent interpretation which explains this discrepancy. Consequently, the problem can not be resolved smoothly.

3. The more compelling stimulus should “win” and be placed in the perceived visual field, overwhelming the less compelling stimulus.

4. The more compelling image is the screen boundary. (That is, the screen boundary has a higher contrast gradient. Possibly it would be useful to formulate this information-theoretically.)

5. Consequently, the screen boundary is placed in the perceived visual field, resulting in the luning effect.

In keeping with Shimojo and Nakayama [95], one might expect that providing the nervous system with an ecologically valid interpretation of why the inconsistency occurs would remove the luning effect. An ecologically valid interpretation can be provided simply by supplying a foreground occlusion mounted close to each eye individually which blocks the view of the nasal screen boundary. The screen boundary is in effect moved close to each eye. Since the boundary is close to each eye, it would
not be expected to be visible by the other eye. Consequently, there is an ecologically valid interpretation concerning why the boundary is visible in one eye but not in the other. One might therefore expect the lunaring effect to be reduced or removed entirely.

Given an HMD with partial overlap, this hypothesis can be tested quite easily. My own observations were made with a Division dVisor (see Section 3.7.3) and the black cap of a Write Brothers Papermate pen (medium point). Holding the cap of the pen under the HMD close to the eye, in such a way as to block the nasal edge of the screen, greatly reduces or eliminates the lunaring effect.

The color of the pen cap was chosen to match the black edge of the screen (and hence the contrast gradient). However, the spatial frequency could not be controlled. That is, a pen cap close to the eye is blurrier than the more distant edge of the screen, and consequently the effectiveness of the pen cap could be attributed to a spatial frequency effect, rather than to the ecological argument².

It is an open question, so far as I know, but I find the ecological interpretation more plausible than the spatial frequency interpretation. The ecological interpretation addresses a real problem which the nervous system must solve (creating a single consistent perceived visual field from binocular input). Furthermore, the ecological argument is consistent with recent findings, described above, that binocular rivalry is a fairly high-level phenomenon.

From the point-of-view of practical HMD design, however, it does not much matter whether one favors the spatial frequency or the ecological interpretation. In addition to presence considerations, described in Chapter 5, the lunaring effect provides a second reason for mounting foreground occlusions in HMD's.

² Dr. Patterson, a visual psychologist at Washington State University specializing in stereovision, has taken the “spatial frequency” position in our own discussions. Ironically, I am in debt to him for the Shimojo and Nakayama [95] reference.
Appendix F

SIMULATOR SICKNESS TERMINOLOGY

There is an ambiguity in the use of the term “simulator sickness”. In informal usage, “simulator sickness” tends to refer to the generic experience of feeling sick as a result of exposure to computer-generated stimuli. However, it is frequently used in a more restricted sense, as including only the sickness caused by poor simulations. For instance, Pausch et al. [74] mention that “The term simulator sickness is typically used to refer to sickness caused by the incorrect aspects of the simulation, not sickness caused by a correct simulation of a nauseating experience, such as a turbulent airplane flight.” Elsewhere in the same special issue on simulator sickness, one may find “simulator sickness” used in the more generic sense. For instance, in the preceding article Biocca [13] states that “Simulator sickness is the term that has been attached to a host of symptoms associated with visual and vestibular disturbances that resemble motion sickness.” The generic usage of “simulator sickness” is implicit in the title of the special issue, “Spotlight On: Simulator Sickness” (covering all sickness symptoms induced by simulators).

To take another example of the generic usage, Kennedy et al.’s widely-used “Simulator Sickness Questionnaire” [55] records motion sickness symptoms.

It appears that there are three ideas present for which only two terms are in widespread use. The best solution is to introduce a third term. The three ideas are:

1. The generic feeling of sickness resulting from exposure to a computer-generated space.

2. The component of “1” which is inherent to the stimulus itself, and which would
be present even if the simulation were a perfect representation of the real world.

3. The component of “1” which results from an imperfect simulation, for instance due to lag, poor inter-ocular adjust, poor resolution, etc.

There is general agreement that “2” should be referred to as “motion sickness”. The problem lies with “1” and “3”. Both are important ideas, and the term “simulator sickness” tends to oscillate between them depending on the topic of discussion. For our own work, Mark Draper and I at the HITL found it convenient to use “simulator sickness” to refer to “1”, and to introduce the term “interface sickness” to refer to “3”. “Simulator sickness” is thus used in the generic sense (“1”) in this dissertation.
Appendix G

SIMULATOR SICKNESS QUESTIONNAIRE

The Simulator Sickness Questionnaire (SSQ) introduced by Kennedy et al. [55] was used as a measure in the simulator sickness experiments of Chapter 6. The symptoms used, and their weightings, are given in Table G (adapted from [55]). The SSQ is based on three components: nausea, oculomotor problems, and disorientation. These can be combined to produce a total SSQ score, as described in Table G.
Table G.1: Computation of SSQ Scores

<table>
<thead>
<tr>
<th>SSQ Symptom</th>
<th>Weight</th>
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<tbody>
<tr>
<td></td>
<td>Nausea</td>
</tr>
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<td>General discomfort</td>
<td>1</td>
</tr>
<tr>
<td>Fatigue</td>
<td>0</td>
</tr>
<tr>
<td>Headache</td>
<td>0</td>
</tr>
<tr>
<td>Eyestrain</td>
<td>0</td>
</tr>
<tr>
<td>Difficulty focusing</td>
<td>0</td>
</tr>
<tr>
<td>Increased salivation</td>
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</tr>
<tr>
<td>Sweating</td>
<td>1</td>
</tr>
<tr>
<td>Nausea</td>
<td>1</td>
</tr>
<tr>
<td>Difficulty concentrating</td>
<td>1</td>
</tr>
<tr>
<td>Fullness of head</td>
<td>0</td>
</tr>
<tr>
<td>Blurred vision</td>
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</tr>
<tr>
<td>Dizzy (eyes open)</td>
<td>0</td>
</tr>
<tr>
<td>Dizzy (eyes closed)</td>
<td>0</td>
</tr>
<tr>
<td>Vertigo</td>
<td>0</td>
</tr>
<tr>
<td>Stomach awareness</td>
<td>1</td>
</tr>
<tr>
<td>Burping</td>
<td>1</td>
</tr>
</tbody>
</table>

Participants report the degree to which they experience each of the above symptoms as one of “None”, “Slight”, “Moderate” and “Severe”. These are scored respectively as 0, 1, 2 and 3. To compute the scale scores for each column, the reported value for each symptom is multiplied by the weight in each column and then summed down the columns. The total SSQ score is obtained by adding the scale scores across the three columns and multiplying by 3.74. Weighted scale scores for each column individually can be found by multiplying the “Nausea” scale score by 9.54; the “Oculomotor” subscale by 7.58; and the “Disorientation” subscale by 13.92.
VITAE

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CITIZENSHIP
Canada and the United Kingdom.
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EDUCATION
Dissertation title: The Role of Rest Frames in Vection, Presence and Motion Sickness.
This thesis was the first study of a pioneering technique for reducing Parkinson’s
disease symptoms using visual displays. The technique has since been the frequent
topic of televised documentaries.

ACADEMIC EMPLOYMENT

OTHER DISTINCTIONS
Top 0.5% on SAT and PSAT (U.S. pre-collegiate tests).
United States and International (FIDE)-rated chess master.

RESEARCH INTERESTS

- Motion sickness and simulator sickness.

- Psychophysical measures for presence.

- Vection.

- Use of motion cues to reduce Parkinson’s disease symptoms.

- Visualization of complex information.

- Online commerce and communities.

- Social implications of technology.

PUBLICATIONS


Prothero, J, Draper, M, Furness, T, Parker, D & Wells, M. The use of an independent visual background to reduce simulator side-effects. Submitted journal article.


INTELLECTUAL PROPERTY


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