

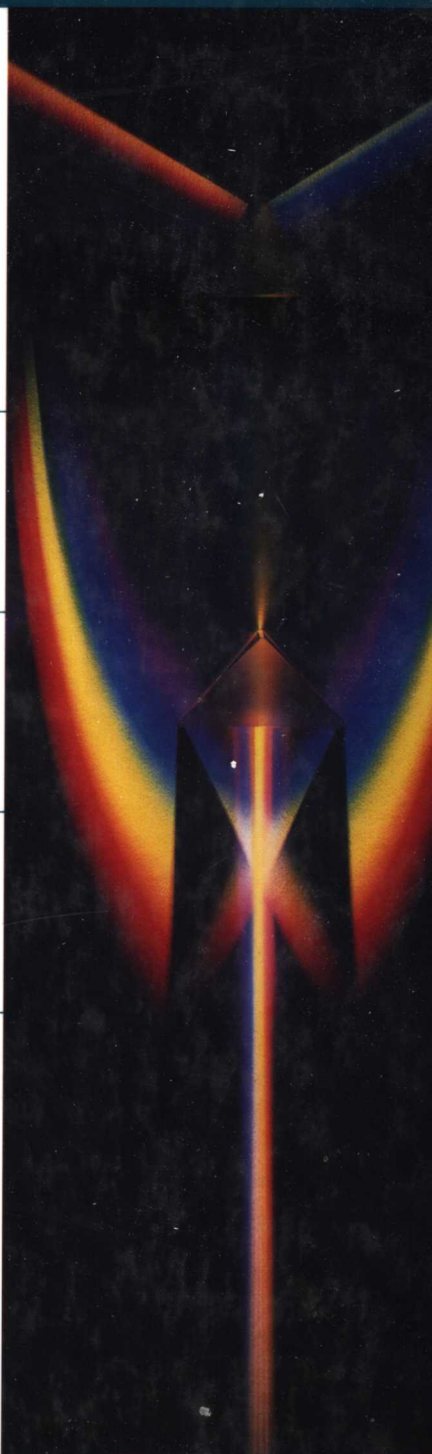
OPTICAL & ELECTRO-OPTICAL
ENGINEERING SERIES

*James E. Melzer
& Kirk Moffitt*

HEAD MOUNTED DISPLAYS

*Designing
for the User*

Robert E. Fischer & Warren J. Smith
SERIES EDITORS



Head-Mounted Displays

Designing for the User

James E. Melzer

Kirk Moffitt

McGraw-Hill

New York San Francisco Washington, D.C. Auckland
Bogotá Caracas Lisbon London Madrid
Mexico City Milan Montreal New Delhi
San Juan Singapore Sydney
Tokyo Toronto

Library of Congress Cataloging-in-Publication Data

Melzer, James E.

Head-mounted displays: designing for the user / James

E. Melzer, Kirk Moffitt.

p. cm. — (Optical and electro-optical engineering series)

Includes bibliographical references and index.

ISBN 0-07-041819-5 (alk. paper)

1. Helmet-mounted displays—Design and construction. 2. Virtual reality. I. Moffitt, Kirk Wayne, 1951– II. Title.

III. Series.

TK7882.I6M45 1997

96-49041

621.39'9—dc21

CIP

McGraw-Hill



A Division of The McGraw-Hill Companies

Copyright © 1997 by the McGraw-Hill Companies, Inc. All rights reserved. Printed in the United States of America. Except as permitted under the United States Copyright Act of 1976, no part of this publication may be reproduced or distributed in any form or by any means, or stored in a data base or retrieval system, without the prior written permission of the publisher.

1 2 3 4 5 6 7 8 9 0 DOC/DOC 9 0 1 0 9 8 7 6

ISBN 0-07-041819-5

The sponsoring editor for this book was Steve Chapman, the editing supervisor was Bernard Onken, and the production supervisor was Pamela Pelton. It was set in Century Schoolbook by Publication Services.

Printed and bound by R. R. Donnelley & Sons Company

McGraw-Hill books are available at special quantity discounts to use as premiums and sales promotions, or for use in corporate training programs. For more information, please write to the Director of Special Sales, McGraw-Hill, 11 West 19th Street, New York, NY 10011. Or contact your local bookstore.

Information contained in this work has been obtained by The McGraw-Hill Companies, Inc. ("McGraw-Hill") from sources believed to be reliable. However, neither McGraw-Hill nor its authors guarantee the accuracy or completeness of any information published herein and neither McGraw-Hill nor its authors shall be responsible for any errors, omissions, or damages arising out of use of this information. This work is published with the understanding that McGraw-Hill and its authors are supplying information but are not attempting to render engineering or other professional services. If such services are required, the assistance of an appropriate professional should be sought.



This book is printed on recycled, acid free paper containing a minimum of 50% recycled de-inked fiber.

Contributors

Preface, Chapter 1: James E. Melzer
Kaiser Electro-Optics
2752 Loker Avenue West
Carlsbad, CA 92008
jmelzer@aol.com

Preface, Chapter 1, Chapter 5: Kirk Moffitt, Ph.D.
79245 Camino del Oro
La Quinta, CA 92253
619/360-0204
macpr@cyberg8t.com

Chapter 2: Robert G. Eggleston, Ph.D.
Fitts Human Engineering Division
Armstrong Laboratory (AL/CFH)
2255 H Street
Wright-Patterson AFB, OH 45433-7022
reggleston@al.wpafb.af.mil

Chapter 3: H. Lee Task, Ph.D.
Fitts Human Engineering Division
Armstrong Laboratory (AL/CFH)
2255 H Street
Wright-Patterson AFB, OH 45433-7022
ltask@al.wpafb.af.mil

Chapter 4: Robert E. Fischer
OPTICS 1, Inc.
3050 Hillcrest Drive, suite 100
Westlake Village, CA 91362
refischer@optics1.com

Chapter 6: Chris E. Perry
Escape and Impact Protection Branch
Armstrong Laboratory (AL/CFBE)
2800 Q Street, Bldg. 824
Wright-Patterson AFB, OH 45433-7022
cperry@al.wpafb.af.mil

Chapter 6: John R. Buhrman
Escape and Impact Protection Branch
Armstrong Laboratory (AL/CFBE)
2800 Q Street, Bldg. 824
Wright-Patterson AFB, OH 45433-7022
jbuhrman@al.wpafb.af.mil

Chapter 7: Jennifer J. Whitestone
Fitts Human Engineering Division
Armstrong Laboratory (AL/CFHD)
2255 H Street
Wright-Patterson AFB, OH 45433-7022
jwhitestone@al.wpafb.af.mil

Chapter 7: Kathleen M. Robinette
Fitts Human Engineering Division
Armstrong Laboratory (AL/CFHD)
2255 H Street
Wright-Patterson AFB, OH 45433-7022
krobinette@al.wpafb.af.mil

Chapter 8: Elizabeth Thorpe Davis, Ph.D.
School of Psychology
Georgia Institute of Technology
Atlanta, GA 30332-0170
ed15@prism.gatech.edu

Chapter 9: David A. Southard, Sc.D.
Charles Stark Draper Laboratory MS-3F
555 Technology Square
Cambridge, MA 02139-3563
southard@draper.com

Chapter 10: Victoria Tepe Nasman, Ph.D.
Logicon Technical Services, Inc.
P.O. Box 317258
Dayton, OH 45437-7258
vnasman@al.wpafb.af.mil

Chapter 10: Gloria Calhoun
Fitts Human Engineering Division
Armstrong Laboratory (AL/CFHP)
2255 H Street
Wright-Patterson AFB, OH 45433-7022
gcalhoun@al.wpafb.af.mil

Chapter 10: Grant R. McMillan, Ph.D.
Fitts Human Engineering Division
Armstrong Laboratory (AL/CFHP)
2255 H Street
Wright-Patterson AFB, OH 45433-7022
gmcmillan@al.wpafb.af.mil

Chapter 11: Jeff Gerth, Ph.D.
Georgia Institute of Technology
Georgia Tech Research Institute
ELSYS/SEV - Human Factors Branch
Atlanta, GA 30332-0840
jeff.gerth@GRTI.gatech.edu

Preface

One of our early experiences with a commercial head-mounted display (HMD) was at an evening reception following a virtual reality conference. Although we had been building military HMDs for several years, this was going to be a new experience. After fortifying ourselves with wine and cheese, it was our turn to view the HMD. We were disappointed. It was front-heavy and uncomfortable. It had a fuzzy appearance, and it did not allow for eyeglasses. When we mentioned this, the man demonstrating the device assured us that it was not the wine and that it would not have made any difference if we *had* worn eyeglasses.

At the same show we had the opportunity to try on a headset that was billed as *the VR HMD*. One of us has a rather large head, and this device did not fit over it. After a quick modification by the vendor, we managed a tight fit, but it was not worth the effort. The imagery was so badly misaligned that viewing it for more than a few moments was painful.

Another experience was a series of meetings we were having with a group of Army flight-safety officers. We wanted them to fly one of our company's HMDs in their helicopter, but first we needed approval from their safety committee. The process took quite some time, because of what we perceived as incessant questions about the most minute details of our design. After a particularly grueling face-to-face session, the meeting broke up and we left with our flight-safety approval. As we were walking out of the building, one of the flight surgeons took us aside. He told us not to take the interrogations personally, because the people we were talking with were the ones responsible for investigating accidents—an unpleasant task, considering how a helicopter crashes.

These three examples show why in designing or buying an HMD we need to understand who the user is, how the user will interact with the display, and what the environment will be like. The first two examples show the results of a lack of this understanding—poorly aligned displays that don't fit. The third shows the results of having that understanding. The flight surgeons learned about the delicate balance between the HMD *as display* and the HMD *as life-support* through their experiences.

An HMD is something you wear *and* something you view. It is a personal device that can provide you with information, train you to do a job by simulating what it would really be like, or entertain you by transporting you to a fantasy world. At the center of these experiences

is the human who wears and views the HMD. Properly designed, an HMD can suspend belief sufficiently to train a pilot to fly an airplane or a surgeon to perform a new operation, or transport you to the surface of Mars. Improperly designed, the HMD can be uncomfortable to wear, difficult to use, and even painful to view.

This is not surprising, as it seems to be the fate of many new technologies when first introduced. One example is the early DOS-based computers. To perform a routine task like saving a file to disk, the user had to enter a string of seemingly unrelated and unintelligible characters. This turned off some people, confused others, and convinced still more that the personal computer was not a solution for everyday tasks.

Early HMDs took a similar path. It was thought that a display on the head was simply that—glass and electronics mounted in front of the eyes, with no serious regard given to what was really needed by the user. Early designers were rushing toward a vision of virtual and interactive imagery, and they placed their emphasis on the technology, not on the user. The result was displays that were uncomfortable to wear and difficult to use. HMDs have received a lot of publicity recently—some good as a result of excellent new applications, and some bad as a result of poor designs that were poorly implemented.

It is for all of these reasons that we decided to focus this book on the fundamental needs of the user. We know that the technology will improve over the next few years—we have seen it change just during the writing of this book—but the human who wears the HMD will not appreciably change over the next several millenia. If we understand what these fundamental needs are, we can take the developments in technology, implement them in our designs, and provide an HMD that will benefit the user. There will still be trade-offs to be made as technology improves, but understanding the user's essential needs will help us make intelligent decisions.

This book is a compilation of the many subjects that relate to the design of HMDs. It is by its nature a multidisciplinary discussion, because to adequately address the needs of the user, we must cross numerous behavioral, psychological, performance, and anthropometric boundaries. The authors of the chapters are experts in their fields with academic, commercial, and military backgrounds and we thank them for their fine work. We hope that this book will benefit both users and designers of HMDs.

We would like to extend our thanks to Kaiser Electronics for support during Kirk Moffitt's tenure with the company, and to Kaiser Electro-Optics for continued support of Jim Melzer. Finally, we would like to thank Warren Smith for his support and guidance during the preparation of this book.

Contents

Contributors	xi
Preface	xv
Chapter 1. HMD Design—Putting the User First	1
1.1 The Richness of an HMD	2
1.2 What Is an HMD?	2
1.3 Early HMDs	4
1.4 User Requirements	8
1.5 Task Requirements	11
1.6 Summary	14
1.7 References	14
1.8 Annotated Bibliography	15
Chapter 2. User-Centered Design in the Trenches: Head-Mounted Display System Design and User Performance	17
2.1 Introduction	18
2.2 User-Centered Design	19
2.3 Applying User-Centered Design Philosophy to HMD System Design	21
2.4 The User Performance Framework in Action	26
2.4.1 Identification of HMD, Task, and User Properties	27
2.4.2 Example of the Three-Step Decision-Making Procedure	29
2.4.3 Facilitating Discovery	34
2.5 Analysis Step	36
2.5.1 Use of Models in the Design Decision-Making Process	36
2.5.2 Detailed Analysis	42
2.6 Final Comments	51
2.7 Acknowledgments	53
2.8 References	53
Chapter 3. HMD Image Source, Optics, and the Visual Interface	55
3.1 Introduction	56
3.2 Basic Optical System Approaches	57
3.2.1 Simple Magnifier	57
3.2.2 Compound Microscope	58
3.3 HMD Optical Characteristics	59
3.3.1 Field of View	60
3.3.2 Image Quality	63
3.3.3 Luminance	70
3.3.4 Eye Relief Distance	72
3.3.5 Exit Pupil (or Eye Motion Box) Size	72
3.3.6 Focus and Accommodation	73

vi Contents

3.4	HMD-Vision Interface Issues	74
3.4.1	Ocularity	74
3.4.2	Superposition with External Scene	75
3.4.3	Field Curvature	76
3.4.4	Distortion	77
3.4.5	Adjustments	78
3.5	Summary	80
3.6	Bibliography	81

Chapter 4. Fundamentals of HMD Optics 83

4.1.	Introduction	84
4.2	Fundamental Parameters	85
4.2.1	Resolution in a Theater	85
4.2.2	Pixel-Based Imagery	86
4.3	Basic Parameters of Head-Mounted Displays	87
4.4	Performance Specifications for HMD Optics	90
4.5	Magnification	90
4.6	Lens Aberrations	92
4.7	Viewing Optics Designs	99
4.8	New Design Forms and Producibility Issues	102
4.9	Summary and Conclusions	104
4.10	References	104
	Appendix: Optical Design Forms	105

Chapter 5. Designing HMDs for Viewing Comfort 117

5.1	Preface	118
5.2	HMD Viewing Comfort	119
5.3	User and HMD Characteristics	122
5.3.1	Visual Acuity and Eye Relief	122
5.3.2	Binocular Balance and HMD Alignment	123
5.3.3	Dark Focus and Vergence	124
5.3.4	IPD and Exit Pupil	125
5.3.5	Eye Dominance	126
5.3.6	Using HMDs to Improve Vision	126
5.3.7	Extent of Eye Movements, Head Tracking, and VOR	126
5.4	Binocular HMD Tolerances and Effects	127
5.4.1	Vertical Alignment	128
5.4.2	Horizontal Alignment	132
5.4.3	Accommodation/Vergence Dissociation with Stereo Displays	135
5.4.4	Rotational Differences	136
5.4.5	Magnification Difference	137
5.4.6	Luminance Difference	137
5.4.7	Changes in Visual Status	138
5.5	Monocular HMD Tolerances and Effects	139
5.6	Motion Effects	139
5.7	Summary	142
5.8	References	142

Chapter 6. HMD Head and Neck Biomechanics 147

6.1	Introduction	148
6.2	Background: Basic Anatomy and Biomechanics	149

6.2.1 Basic Anatomy	149
6.2.2 Basic Biomechanics	151
6.3 Static Effects	154
6.4 Dynamic Effects	157
6.4.1 Ground Vehicle Environment	158
6.4.2 Aerospace Environment	159
6.5 Conclusions	169
6.6 References	171

Chapter 7. Fitting to Maximize Performance of HMD Systems 175

7.1 Introduction	176
7.2 Anthropometric Myths: Methods That Don't Work	177
7.2.1 Using Percentiles: The Impossible Dream	177
7.2.2 The Frankfurt Plane: An Oldie but not a Goodie	179
7.2.3 Line of sight: More Mystery than Myth	181
7.2.4 Sizing before design: Building the Cart Without Measuring the Horse	184
7.3 Current Practices: Methods That Work	188
7.3.1 Three-Dimensional Scanning: Giving Designers X-ray Vision	188
7.3.2 Feature envelopes: Marking the Boundaries	189
7.3.3 Fit testing: The Right Data at the Right Time	193
7.4 Looking Ahead: Put Away Those Tape Measures	198
7.4.1 Defining Line of Sight	198
7.4.2 Generic Head Alignment	198
7.4.3 Biofidelic Computer-Aided Design Head	199
7.5 Summary	199
7.6 References	200
Appendix: Traditional Anthropometric Measures for the Head and Face with Minimal System Dependence	203

Chapter 8. Visual Requirements in HMDs: What Can We See and What Do We Need to See? 207

8.1 Simulated Visual Displays versus Real-World Perception	208
8.2 Characteristics of the Human Visual System and Their Relation to the Visual Displays of Immersive and See-Through HMDs	209
8.2.1 Brightness and Contrast	209
8.2.2 Visual Acuity and Spatial Resolution	212
8.2.3 Critical Flicker Fusion (CFF), Temporal Resolution, and Motion	219
8.2.4 Field of view (FOV)	222
8.2.5 Binocular HMDs versus Monocular or Biocular HMDs	225
8.2.6 Color versus Monochrome	231
8.3 Perception and Performance Issues	235
8.3.1 What Is It and Where Is It?	236
8.3.2 Immediate Performance Benefits versus Long-Term Comprehension	238
8.3.3 Fidelity versus Technical Limitations Issues	239
8.3.4 Laboratory Research versus Field Studies of Perception and Performance Issues with HMDs	240
8.3.5 Examples of HMD Tasks Involving Perception and Performance Issues	241
8.4 Summary and Conclusions	246
8.5 References	248

Chapter 9. Designing HMD Systems for Stereoscopic Vision	253
9.1 Introduction	254
9.1.1 The Problem	254
9.1.2 Design Goals	254
9.2 Background	255
9.2.1 Computers and Stereoscopy	255
9.2.2 Applications for Stereoscopic HMDs	256
9.3 Characteristics and Limitations of Stereoscopic HMDs	258
9.3.1 Advantages	259
9.3.2 Pitfalls	260
9.3.3 Performance Issues	263
9.3.4 User Acceptance	264
9.3.5 A Systems Approach to HMD Design	265
9.4 Challenges for Successful Design	266
9.4.1 Matching Human Vision	266
9.4.2 Perspective	269
9.4.3 Field of View	270
9.4.4 Range of Depth	271
9.4.5 Rotated Perspective	273
9.5 Simulating Stereoscopic Vision	273
9.5.1 Recommended Method	274
9.5.2 Matrix Operators	275
9.5.3 Viewing Algorithm	277
9.6 Conclusion	281
9.7 References	281
Chapter 10. Brain-Actuated Control and HMDs	285
10.1 HMDs: The Need for Control Alternatives	286
10.2 Brain-Actuated Control: A Unique Control Technology	287
10.2.1 History and Background	290
10.2.2 Endogenous versus Exogenous Control Signals	291
10.2.3 Current Status of BAC: Research and Performance	293
10.3 Potential Applications of BAC	297
10.4 BAC: Systems Engineering and Technology	299
10.4.1 Signal Acquisition and Processing	299
10.4.2 Control Algorithms and Feedback Displays	301
10.5 BAC and HMDs	302
10.5.1 EEG-Based Command and Control	302
10.5.2 System Operations Feedback	306
10.6 Conclusions and Recommendations	307
10.6.1 Research and Development Strategies	307
10.6.2 Technology Transfer Priorities and Issues	309
10.7 References	310
Chapter 11. Design Issues in Human Performance-Based Test and Evaluation of HMDs	313
11.1 Introduction to the Human Performance Test and Evaluation Process	314
11.1.1 What is a Test and Evaluation Process?	314
11.1.2 Basics of Performance Testing	316
11.1.3 HMD Users, Setting, and Scenarios of Use	316
11.1.4 HPT&E Test Goal	318

11.2	Testing HMDs	319
11.2.1	Essential Content Areas	319
11.2.2	Establishing the Test Focus	321
11.2.3	Interviewing Potential Users and SMEs	324
11.2.4	Performance Testing	326
11.3	Conclusions	333
11.4	References	335
Chapter 12. Glossary of HMD Terms		337
Index		349

HMD Design— Putting the User First

James E. Melzer

Kirk Moffitt

1.1 The Richness of an HMD	2
1.2 What Is an HMD?	2
1.3 Early HMDs	4
1.4 User Requirements	8
1.5 Task Requirements	11
1.6 Summary	14
1.7 References	14
1.8 Annotated Bibliography	15

The head-mounted display (HMD) is a critical link in virtual-environment and visually coupled systems. HMD users can experience immersion in computer-generated virtual environments, privately view a movie, perform a delicate endoscopic surgical procedure, or fly an attack helicopter nap-of-the-earth in darkness. The success of these tasks depends on the design of the HMD system. Given the intimate interface to the human, the user should be the central focus of the design process. An HMD will be successful only if full consideration is given to the characteristics and tasks of the user.

1.1 The Richness of an HMD

The head-mounted display (HMD) provides the user with a set of capabilities that conventional displays cannot duplicate. An HMD can be personal, interactive, expansive, *and* virtual. Handheld televisions and video games, personal computer monitors, panoramic theater screens, and head-up displays share one or two of these attributes at most. Only an HMD provides the user with an intimate display that can be reactive to head and body movement and surround him or her with a virtual environment that extends far beyond the confines of the miniature image source.

Unlike televisions, computer monitors, and movie screens, which usually vary only in size, HMDs come in many types that accommodate a wide range of uses. An HMD can be any of the following:

- A simple reticle projector that a pilot uses to designate an enemy aircraft
- A more thorough symbology display that gives the pilot orientation and status information
- A small offset display that a technician can glance at for reference data
- A private view of a selected movie by an airline passenger
- Stereo imagery relayed from head-steered cameras located on a remote vehicle
- A computer-generated, panoramic world that can be navigated with simple movements and gestures

This wealth of applications makes a book on HMD design worthwhile. It is not our intent to provide a formula for building each variation, but rather to engage the reader in a discussion of fundamental HMD design concepts that center on the characteristics and capabilities of the user. The chapters in this book cover topics as diverse as fitting HMDs to human heads, perceptual requirements of HMDs, and incorporating brain-actuated control into HMDs. The common thread is the need to put the user at the center of the design process.

1.2 What Is an HMD?

In its simplest form, an HMD consists of an image source and collimating optics in a head mount (see Fig. 1.1). The HMD can then become more elaborate in several ways. There may be one or two display channels. These channels may display graphics and symbology with or without video overlay. They may be viewed directly and occlude external vision for a fully immersive experience, or they may use a

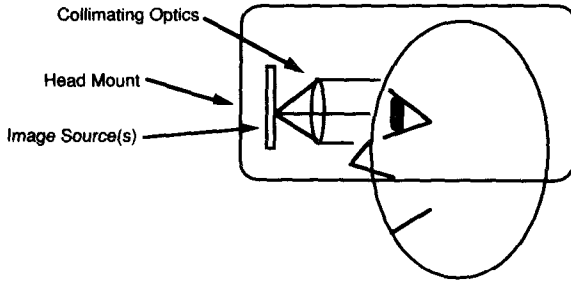


Figure 1.1 An HMD consists of an image source, collimating optics, and a head mount—providing a virtual image to the wearer.

semitransparent combiner with see-through to the outside world. In this augmented reality mode, the HMD may overlay symbology or other information on the world view.

The HMD image source may be a CRT or LCD mounted on the head, or the image may be brought up to the head through a fiberoptic bundle. An HMD may use a simple headband for mounting on the head, or the optics and the displays may be integrated into an aviator's flight helmet. This latter device is a specialized case of the head-mounted display—the *helmet-mounted display*.

The HMD is part of a larger system that can include an image generator, a head tracker, audio, and a manual input device (see Fig. 1.2). The image generator may be a sophisticated image rendering engine or a personal computer. A tracker, which communicates the orientation of the user's head to the image generator, immerses the user in a virtual environment. This immersion is often enhanced by 3D or directional audio. Input/output devices can include brain- or voice-actuated control, a joystick, and a 3D mouse or glove to manipulate virtual objects.

Properly designed, this deceptively simple arrangement of optics and electronics can fit comfortably and be worn for several hours. It can instruct you in new ideas, provide important information, or transport

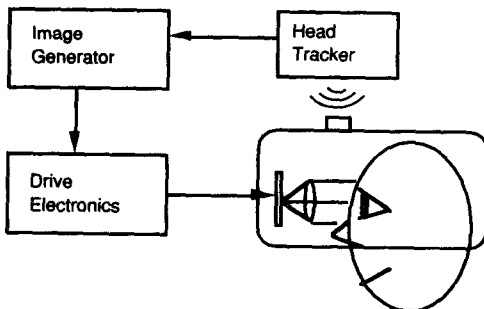


Figure 1.2 An HMD is part of a visually coupled display system consisting of an image generator, drive electronics, and a head tracker.

you to alternative realities. Improperly designed, an HMD can quickly strain your eyes, your neck, or your stomach with symptoms that can last for several hours. Why? Our evolutionary development occurred in the natural world, with the neck supporting only the head and with visual imagery being perfectly aligned and correspondent. HMDs can place a burden on the neck, can easily be misaligned, and may put the visual and vestibular systems into conflict.

These are many diverse, complex, and interdisciplinary issues that are associated with the design of an HMD. Some are subtle; some are obvious. All are centered on the needs of the users, who will be wearing the device, and the tasks they are performing. If we ignore these needs, we will produce an HMD that can have negative side effects that will not be accepted. Only by understanding the users and treating them as an integral part of the process can we assure a successful design.

1.3 Early HMDs

In the 1960s Ivan Sutherland married CRTs with focusing optics, head orientation hardware, and an early computer image generator to produce the first HMD system. Because of the weight, Sutherland suspended it from the ceiling, from which it got the name "Sword of Damocles" (Rheingold, 1991). Sutherland used this system to conduct early experiments in virtual environments and HMD-based stereo-vision with a wide-field-of-view binocular display.

The U.S. military briefly experimented with helmet-mounted sights in the 1970s. The Visual Target Acquisition System, or VTAS, was a simple HMD used to aim air-to-air missiles. It was a lightweight device that attached to a standard flight helmet, and it reflected light from a series of light-emitting diodes off a special visor. Unfortunately, the VTAS was abandoned because of the limitations in missile technology at that time (Dornheim, 1995b).

Improvements in HMD technology and their applications proceeded slowly until the mid 1980s, when there were four key HMD developments.

First, researchers at NASA Ames Research Center developed their Virtual Interactive Environment Work Station (VIEW), consisting of a wide-field-of-view (WFOV), head-tracked HMD with 3D virtual sound connected to a computer image generator. This HMD design, shown in Fig. 1.3, used two commercial LCD image sources with projector lenses, and it looked like an oversized scuba mask. It provided the wearer with visual and audio feedback in a WFOV immersive environment, but with low resolution. This HMD design became synonymous with the emerging technology of virtual reality, and variations of this design were sold through the mid 1990s.