Human Factors in Transportation

Principles and Practice of Aviation Psychology

Edited by

Pamela S. Tsang • Michael A. Vidulich

PRINCIPLES AND PRACTICE OF AVIATION PSYCHOLOGY

HUMAN FACTORS IN TRANSPORTATION

A Series of Volumes Edited by
BARRY H. KANTOWITZ

Barfield/Dingus • *Human Factors in Intelligent Transportation Systems*

Billings • *Aviation Automation: The Search for a Human-Centered Approach*

Garland/Wise/Hopkin • *Handbook of Aviation Human Factors*

Hancock/Desmond • *Stress, Workload, and Fatigue*

Noy • *Ergonomics and Safety of Intelligent Driver Interfaces*

O'Neil/Andrews • *Aircrew Training and Assessment*

Parasuraman/Mouloua • *Automation and Human Performance: Theory and Application*

Tsang/Vidulich • *Principles and Practice of Aviation Psychology*

Wise/Hopkin • *Human Factors in Certification*

For more information about LEA's Human Factors in Transportation series, please contact Lawrence Erlbaum Associates, Publishers, at *www.erlbaum.com.*

PRINCIPLES AND PRACTICE OF AVIATION PSYCHOLOGY

Edited by

Pamela S. Tsang
Wright State University

Michael A. Vidulich
Air Force Research Laboratory

LAWRENCE ERLBAUM ASSOCIATES, PUBLISHERS
2003 Mahwah, New Jersey London

Senior Acquisitions Editor:	Anne Duffy
Editorial Assistant:	Kristen Duch
Cover Design:	Kathryn Houghtaling Lacey
Textbook Production Manager:	Paul Smolenski
Full-Service Compositor:	Black Dot Group / An AGT Company
Text and Cover Printer:	Sheridan Books, Inc.

Cover photo courtesy of Daryl Chapman. Final approach to Hong Kong's Kai Tak airport during its final days of operation. Despite the exacting and least forgiving challenge of negotiating a wide body jet amidst precipitous terrain and hair-raisingly close highrises, pilots have routinely landed safely for many years.

This book was typeset in 10/12 pt. Times Regular, Italic, and Bold. The heads were typeset in Americana Bold and Times Italic.

Lawrence Erlbaum Associates, Inc., Publishers
10 Industrial Avenue
Mahwah, New Jersey 07430

Library of Congress Cataloging-in-Publication Data

Principles and practice of aviation psychology / edited by Pamela S. Tsang, Michael A. Vidulich.
p. cm. — (Human factors in transportation)
Includes bibliographical references and index.
ISBN 0-8058-3390-0
1. Aviation psychology. I. Tsang, Pamela S. II. Vidulich, Michael A. III. Series.
RC1085 .P75 2002
629.132'52'019—dc21 2002024377

Books published by Lawrence Erlbaum Associates are printed on acid-free paper, and their bindings are chosen for strength and durability.

Printed in the United States of America
10 9 8 7 6 5 4 3 2

To my parents, Michael and Pansy,
for their wisdom
and
to my grandmothers, Yeung Guk, Lee Sui Woo, Chu Hew Fa, and Lai Sui Kim
for their fortitude
—Pamela S. Tsang

To my parents, Joseph and Therese,
for their love and support
—Michael A. Vidulich

This page intentionally left blank

Contents

Preface xvii

Foreword xix

Series Foreword xxiii

Abbreviations xxv

1 **Introduction to Aviation Psychology** 1
Pamela S. Tsang and Michael A. Vidulich
The Changing Role of the Pilot 1
  Early Beliefs of the Pilot's Role in Aviation 1
  The Birth of Scientific Aviation Psychology 2
  The Modern Role of the Pilot 4
  Visualizing the Future Pilot 8
The Roles of Basic and Applied Research in Aviation Psychology 9
  Basic and Applied Research in Meeting Future Needs 9
  The Role of Basic Research and Theory in Aviation Psychology Practice 10
Preview of the Chapters 12
References 18

2 **Perception and Attention During Low-Altitude High-Speed Flight** 21
Ralph Norman Haber and Lyn Haber
Aerodynamics of Motion: The Effects of Control Inputs on Flight 23
  Descriptions of the Position and Movements of Aircraft in Relation to Control Inputs 24
  Some Sample Maneuvers and Their Associated Time-to-Die and Free Time 26

Sources of Information That Specify Ground Clearance 32
  Visual Information From the Surface of the Terrain 33
  Vestibular Information Arising From Changes in G-Forces 39
  Symbolic Information From Flight Instruments and Displays 40
  Information Acquired Before the Flight 42
Perceptual Processes: How a Pilot Perceives Ground Clearance 44
  Automatic and Controlled Perceptual Processes 44
  Perceiving a Change in Altitude AGL 46
  Perceiving Absolute Altitude AGL 50
  Perceiving the Velocity Vector in Straight and Level and in Turning Flight 51
  Perceiving Ground Track 55
  Perceiving Distance to Objects in Front of the Plane 56
Integration of Tasks and Priorities in Low-Altitude Flight 57
  Factors That Affect the Difficulty of Flight Tasks 58
  Factors That Affect the Duration of Tasks 59
  Free Time 62
  A Training Program to Integrate Low-Altitude Tasks With All Other Mission Tasks 64
Conclusion 65
References 66
Acknowledgments 68

3 Spatial Orientation 69
Laurence R. Young
Sensory Bases for Spatial Orientation 72
  Visual System 72
  Vestibular System 73
  Other Proprioceptive Sensors 80
  Auditory Spatial Orientation 81
  Multisensory Interaction 82
Spatial Disorientation Illusions 84
  Illusions Attributable Primarily to the Semicircular Canals 84
  Ancillary Effects on SD Illusions 89
  Illusions Attributable Primarily to the Otolith Organs 91
  Visual Illusions 94
Motion Sickness 99
  Causes of Motion Sickness 100
  Simulator Sickness 101
  Drug Treatment 102
Space Flight 102
  Launch 103
  Early-On Orbit 103
  Extravehicular Activity 105
  Artificial Gravity 105

Reentry 106
Postflight Disturbances 106
Major Factors Contributing to SD 107
Night Flying 107
Shifting Reference Frames and Instrument Flying 107
Flight Maneuvers and Head Movements 107
Workload and Capacity 108
Methods to Minimize SD 108
Training to Deal With Spatial Disorientation 108
Cockpit and Instrument Design to Minimize SD 109
References 109

4 Mental Workload and Situation Awareness: Essential Concepts for Aviation Psychology Practice 115
Michael A. Vidulich
Defining Mental Workload and Situation Awareness 116
Types of Theoretical Concepts 118
Models and Measures of Mental Workload and Situation Awareness 121
Secondary Task Measurement of Mental Workload 122
Memory Probe Measurement of Situation Awareness 129
Is There a Relationship Between Mental Workload and Situation Awareness? 133
Future Directions for Mental Workload and Situation Awareness: Research and Applications 137
Meta-Measures and Their Uses 137
Real-Time Human Engineering 138
Conclusion 140
References 142

5 Aviation Displays 147
Christopher D. Wickens
Display Principles 148
Principle of Information Need 148
Principle of Legibility 149
Principle of Display Integration/Proximity Compatibility Principle 149
Principle of Pictorial Realism 152
Principle of the Moving Part 152
Principle of Predictive Aiding 153
Principle of Discriminability: Status Versus Command 154
Summary and Conclusion 155
Classic Navigation: The Historic Perspective 155
Present Navigational Display Environments 157
Display Integration: The Navigational Display 158
Ground Proximity Warning System (GPWS) 160

  The Traffic Alert and Collision Avoidance System (TCAS) **161**
  Conclusions: Cockpit Hazard Warning Systems **162**
  Hazard Alerting: The Alarm Issue **162**
Display Overlay, Integration, and Clutter **164**
Procedural Displays: Text, Instrumentation, Checklists **169**
Advanced Display Technology: 3-D Displays **171**
  Information-Processing Mechanisms **173**
  Aviation Tasks: The Task-Viewpoint Interactions **175**
  3-D Displays: Conclusions and Solutions **178**
Advanced Technology: See-Through Displays: The HUD and the HMD **181**
  The Head-Up Display **182**
  The Helmet-Mounted Display **185**
Automation and Displays **186**
  Display Implications of Aircraft Automation and Autopilots **186**
  Harnessing Automation for Improved Displays **189**
Conclusion **192**
References **192**
Acknowledgments **200**

6 Aeronautical Decision Making: Metaphors, Models, and Methods **201**
David O'Hare

Gamblers, Daredevils, Aces, and Romantics **202**
What Is Aeronautical Decision Making (ADM)? **203**
The Decision Maker as Faulty Computer **204**
The Decision Maker as Rational Calculator **208**
  The Vigilant Decision Maker **210**
  Training Rational Decision Making **211**
  Effects of Technology on Rational Decision Making **213**
The Adaptive Decision Maker **215**
The Decision Maker as Character Defective **217**
The Decision Maker as Enquiring Expert **220**
  Expertise in ADM **223**
The Decision Maker as Organizational Cog **228**
Conclusion **230**
References **232**
Acknowledgments **237**

7 Pilot Actions and Tasks: Selection, Execution, and Control **239**
Christopher D. Wickens

Task Choice and Task Management **239**
  Cockpit Task Management **241**

Concurrent Activities 245
Aviation Control 249
Control Order and Lag 252
Gain and Instability 256
Simplifications 257
Positive Feedback 257
Adaptive Flight Control 259
Flight Control and Task Management 260
Conclusion 260
References 260

8 Pilot Control **265**
Ronald A. Hess

The Aircraft Control Problem 265
Pilot Models 268
Chapter Overview 269
The Feedback Paradigm in Pilot Control 269
Mathematical Preliminaries and Inner-Loop Pilot Control 269
Outer-Loop Pilot Control 279
Historical Perspectives 284
Human Sensors, Control Effectors, and Information Processors 286
Control–Theoretic Models of Pilot Control Behavior 287
Isomorphic Models 287
An Algorithmic Model 296
Utility of Control–Theoretic Pilot Models 298
An Example Pilot/Vehicle Analysis 300
The Task and Pilot Model 300
The Input to the Pilot/Vehicle System 304
Predicted Pilot/Vehicle Performance and Handling Qualities 304
Automation and Pilot Control 307
Concluding Remarks 308
References 308

9 Automation and Human Performance in Aviation **311**
Raja Parasuraman and Evan A. Byrne

Background 311
Factors Contributing to Effective Human-Automation Interaction 312
Overview of Chapter 313
Aviation Automation 314
Definition 314
Trends in Aviation Automation 315
A Model for Types and Levels of Human Interaction With Automation 317
Automation-Related Incidents in Aviation 320
Accident Investigation 320

"Fail Silent" Problems and Unforeseen Limits 321
Misuse of Automation 322
Misunderstanding or Lack of Understanding of System 326
Human Performance in Automated Systems 327
Situation Awareness 328
Decision Biases 330
Trusts in Automation 330
Mental Workload 335
Adaptive Automation 338
Characteristics of Adaptive Systems 338
Techniques for Adaptive Automation 339
Benefits of Adaptive Automation 341
Computational and Formal Methods for Studying Human-Automation Interaction 344
Standard and Fuzzy Signal Detection Theory 345
Expected-Value Models 346
Other Formal Models 347
Conclusion 348
References 349
Acknowledgments 356

10 Pilot Selection Methods 357
Thomas R. Carretta and Malcolm James Ree
What Is Pilot Selection and Why Is It Important? 358
Overview of Pilot Selection Process 358
Are Effective Pilots "Selected" or "Trained?" 359
Validity and Validation Studies 359
What Is Validity? 359
What Is a Validation Study? 360
Common Methodological Issues in Pilot Selection 362
Misunderstanding Constructs 362
Lack of Statistical Power 363
Failure to Cross-Validate 364
Misinterpretation of Correlations and Regression 365
Recommendations for Researchers and Practitioners 369
Military Pilot Selection 370
Historical Overview 370
Recent Validation Studies 371
Current Research 378
Commercial Pilot Selection 383
The Future of Pilot Selection Methods 386
General Cognitive Ability 386
Flying Knowledge and Skills 387
Incrementing the Validity of g 387
Conclusion 388

References 389
Acknowledgments 396

11 Training 397
John Patrick

Trends and Contexts of Pilot Training 398
Increasing Automation 399
Crew Coordination 401
Stages of Training Development 402
Analyzing Tasks and Identifying Training Needs 405
Traditional Task Analysis 407
Analysis of Incidents and Errors 409
Training Objectives 412
Training Design 414
Development of Expertise and Transfer 414
Transfer Principles 416
Design of Simulations 419
Design of Practice 422
Evaluation of Training 428
Conclusion 429
References 430

12 Flights of Fancy: The Art and Science of Flight Simulation 435
Mary K. Kaiser and Jeffery A. Schroeder

The Purpose of Flight Simulation 437
Training, Selection, and Testing 438
Research and Development 439
Fidelity of Flight Simulators 439
Validating Simulator Fidelity: How Good Is Good Enough? 440
Flight Simulators: A Brief History 442
Early Efforts 442
A Systematic Approach 442
The Modern Era 443
Visual Systems 443
Characterizing the Visual Capabilities of the Pilot 444
Modeling the Visual Information of the Flight Environment 446
Motion Systems 453
Nonvisual Motion Sensory Capabilities 453
How Motion Systems Work 454
The Platform Motion Debate 458
Recommendations for Further Work 465
Future Fancies 466
References 467

13 **Applying Crew Resource Management Theory and Methods to the Operational Environment** **473**

Paul J. Sherman

One Flight Segment, Several Incidents **473**
Crew Resource Management—Its Theoretical and Applied Genesis **476**
The Paradigm Shift **476**
The Systems Perspective: Modeling Group Inputs, Processes, and Outputs **477**
The Model as Applied to Aviation: Characteristics and Model Dynamics **478**
Applying the IPO Model to Flight-Deck Team Training **481**
Early Approaches to Improving Team Performance on the Flight Deck **483**
Refinement of CRM Training **483**
Measuring CRM Training Efficacy **485**
Attitude Measurement and Its Use in CRM Training **485**
Performance Evaluation: Expert Ratings in the Simulator and on the Line **489**
Further Refinement of CRM Concepts **492**
The Growth of Systemic Evaluation Methods **493**
Applying Current Thinking to the Flight Observation **494**
Automation on the Flight Deck—Another Potential Source of Safety Threats **497**
Automation and Aircrews **497**
Group Communication and Coordination Effects **498**
Automation as Crew Member **499**
Incorporating Automation Issues Into CRM Training **500**
Concluding Remarks **501**
References **501**
Acknowledgments **506**

14 **Assessing Cognitive Aging in Piloting** **507**

Pamela S. Tsang

About the Age 60 Rule **508**
Cognitive Demands of Piloting and Aging **509**
Attention Switching **510**
Attention Sharing **512**
The Expertise Advantage **517**
Characterizing Expertise **517**
The Paradoxical Relationship Between Age and Expertise **518**
Circumventing Intrinsic Processing Limitations **520**
Methodological Issues **522**
Metrics of Pilot Performance and Experience **522**

Cross-Sectional and Longitudinal Methods for Assessing Age Effects 524
Confounds of Age and Experience 525
Generalizing Laboratory Findings to Real-World Operations 527
Summary 529
Manifestation of Aging in Simulator Performance and Accident Data 529
Flight Simulator Performance 529
Accident Data 532
Toward a Better Understanding of the Interplay Between Aging and Piloting 535
Does Age Affect Piloting? 535
The Paramount Role of Experience/Expertise 536
An Empirical Approach 536
Conclusion 538
References 540
Contributors 547
Author Index 553
Subject Index 573

Preface

This book has two main objectives. First, to serve as a training tool for a graduate-level course in aviation psychology or more generally in engineering psychology. In aviation psychology, aviation is the domain of interest; in the engineering psychology, aviation serves as a context on which psychological principles are applied. The book aims at introducing psychological principles and research that are important in aviation; however, principles such as that of human perceptual and attentional capabilities and limitations can certainly be applied to contexts other than aviation. Second, we hope the research findings and applications in aviation psychology presented will be interesting and useful to academic researchers as well as professionals from the industry and government.

Chapters are arranged by important topics in aviation psychology, but they are by no means the only important topics. Given that selection is necessary, our focus is on the pilot in the cockpit (as opposed to the entire aviation system). The impact of technology on piloting and the strategies and approaches aviation psychology as a field can take to meet this ever-changing challenge in the future is another underlying theme.

Our goal is to present state-of-the-art knowledge in the various topics chosen for the book. To this end, we invited experts to author chapters in the area of their expertise. One concern was how the chapters might come together as a coherent treatment of the selected scope of the field; we think that the readers will find minimum redundancy across chapters and the many cross-references between chapters will illustrate how the various topics are interrelated. While the order of the chapters makes sense to us, we do not think it necessary to follow the order presented in the book as each chapter is a complete document on its own.

An important step in the creation of this book was the review process to which each chapter was subjected. We express our deepest appreciation to our reviewers for their generous, constructive contribution of their expertise. Their high-caliber reviews have greatly enhanced the quality and clarity of the final product. We thank: Herbert Bell, Charles Billings, Eugene Burke, Bob Cheung, Francis Durso, Robert Ginnett, Ralph Haber, David Hardy, Keith Hendy, David Hunter, Paul Jacques, Richard Jensen, Raymond King, Steve Landry, William Levison, Monica Martinussen, Grant McMillan, Todd Nelson, Tomas Nygren, Richard Pew, Fred Previc, Amy Pritchett, Roy Ruddle, Robert Shaw, Dominic Simon, Michael Skinner, Robert Taylor, and Christopher Wickens.

The project took much longer than we could have imagined, but we also learned far more than we could have hoped. We thank our authors for sharing their expert knowledge and professional experience. We are in debt to their guidance, cooperative spirit, and patience throughout the production process. We have learned greatly from them.

We are most happy that Captain Neil Johnston consented to write the foreword to this book. His considerable experience as a pilot and a researcher makes him a uniquely appropriate person to provide perspective on the field of aviation psychology.

We would also like to thank Barry Kantowitz, the series editor, Anne Duffy, and other editors and staff at Lawrence Erlbaum Associates for their cheery prompting, their patience, and their guidance and assistance.

Pamela gratefully acknowledges the grant support from the National Institute of Aging, the Ohio Board of Regents, and the National Science Foundation during the course of preparing the book for publication.

Foreword

As someone with a long-standing interest in aviation psychology, I was delighted to be asked to write the foreword to *Principles and Practice of Aviation Psychology*. My personal interest in aviation human factors dates back to my days as an airline copilot in the late 1960s, when I quickly became aware that there was more to aviation than basic stick and rudder skills. I was fortunate to become actively involved in various human factors endeavors in the early 1970s, before the roles of human factors and aviation psychology were accepted as valid by the aviation industry or even by most legislators and safety specialists. Reflecting back on that time, it is hard to believe the extent to which the aviation industry, with its predominant technical focus, was insulated from the outside world. As a result of this isolation, the internal battle to break down prejudices against aviation psychology and human factors took some time to complete. On the other hand, success, when it did arrive, was decisively achieved within a relatively short time.

The key initiative of that era was launched in 1975 at the 20th Technical Conference of the International Air Transport Association (IATA). The official report of the conference subsequently claimed that it had established "...a major and very important change in attitude in the industry towards certain classes of accidents." The world's aviation industry announced two important strategic policy changes at the conference: (a) the official end of the mindless attribution of "pilot error" following accidents and (b) a parallel need to involve those from outside the aviation industry who have expertise in the human sciences.

At that time there were no specialist conferences dedicated to aviation psychology or any specialist books on the subject. The first such book, by Stan Roscoe, appeared in 1980 and was intended for university students. The first dedicated aviation human factors textbook, by Frank Hawkins, followed some seven years later. Hawkins' book was intended to meet the needs of both university students and practitioners, and its appeal continues to this day. While it was an important and groundbreaking text in many ways, most practitioners felt Hawkins' book was too academic to enable them to draw practical training benefits from its contents. However, it was an important initiative, and it performed the valuable service of correctly anticipating the direction in which we needed to go.

Throughout the 1980s there was a steady growth of interest in human factors and a most welcome interaction between various research communities and those involved on a day-to-day basis within the industry. This interaction was greatly facilitated by events such as the active involvement of NASA in air carrier research projects and the inauguration of the first international aviation psychology conference (in 1981). This interaction has, I believe, continued to be of considerable benefit to both communities. Since the start of the 1990s, we have seen a rapid growth of interest in human factors and aviation psychology. The range of publications, conferences, and breadth of topics addressed has become almost overwhelming, and we have moved to the point where it would be a full-time job just to keep track of them all.

I make these introductory remarks by way of welcoming the publication of *Principles and Practice of Aviation Psychology* and with the specific objective of acknowledging just how far we have come in such a short period. These initial observations may also serve to remind us how easy it would be to take for granted the range and depth of the contents of this book. A brief perusal of the contents will quickly establish that it contains a comprehensive and wide-ranging treatment of a domain that has seen a progressive deepening of understanding and sophistication.

We may, for example, take it for granted that all the chapters incorporate credible and relevant aviation examples and applications, appropriately embedded within broad and solid theoretical foundations. That we have steadily advanced to a position where we can achieve this state of affairs should not blind us to the editors' success in actually achieving such a worthy goal. Each chapter is rooted in the "real world" of aviation and performs the valuable service of presenting us with solid theoretical discussions that combine applied relevance and practical insights. I also found helpful and instructive the discussion of the many issues or areas of contention that have not been tackled in the different domains of aviation psychology. By way of example, one might consider the comprehensive treatment of the "platform motion debate" in the chapter on flight simulation by Kaiser and

Schroeder or the discussion of issues relating to pilot selection in the chapter by Carretta and Ree.

As outlined in the first chapter, the development of the discipline of aviation psychology is intimately tied to the historical development of aviation and, in particular, the problems that this development has fostered. The capabilities of aircraft changed radically over the course of the last century, and the role of the pilot—along with others in the aviation system—has necessarily changed in parallel. New challenges for aviation psychology arise with each change in the role and function of pilots and others within the aviation domain. It has been well identified that this trend is seen at its most "cognitively opaque" in the context of the gradual distancing of pilots from direct control of their aircraft. Interaction with automation increasingly demands more sophisticated—or at least "different"—cognition and cockpit management techniques. The contents of this book pay due homage to this trend, especially in respect of developments and issues in automation design and cockpit teamwork.

As evidenced by the content of the different chapters, a healthy interaction between the world of practice and the world of theory works to the advantage of both practitioners and theorists. In this context I particularly welcome the overall orientation and tone of this book, especially because this orientation appeals directly to an enduring bias of my own. Aviation psychology that narrowly treats the applied world as simply providing empirical data to validate theoretical constructs is as impoverished as a world of practice that denies any value to the world of theory. The necessity and value of a dialogue between the two domains is thoroughly endorsed by what the authors of the various chapters have said. I remember only too well the total irrelevance to aviation of most of the sterile theoretical material on decision making available in the 1970s and 1980s. Those involved in university-based research were, for the most part, remarkably uninterested in the challenges presented by real-world problems (or, indeed, by any real-world data that might cast a jaundiced eye on their theoretical framework). The chapter by David O'Hare on aeronautical decision making provides ample testimony as to how far one can advance by virtue of a healthy interaction between the university, research, and applied communities. This example serves to underline the fact that each chapter provides ample evidence of the benefits of such a healthy interaction between these three communities. Furthermore, the contents provide ample testimony as to how this has worked to the advantage of all interested in aviation psychology and human factors.

Moreover, this book has manifestly benefited from the talents of a group of notably experienced and distinguished authors, each providing the reader with a comprehensive and valuable introduction to the various subject areas. In addition to the strengths discussed above, I might also add that much of the discussion within each topic area is set within an appropriate historical context. This assists the reader in understanding how the domain in question has developed in parallel with the demands of aviation itself.

There is a lot to be learned from this book. I congratulate all involved for their manifest success in creating such a comprehensive, relevant, and interesting text. I am grateful to the editors for giving me the opportunity to write this foreword, and I wish both the editors and this excellent book every success in the years to come.

Captain Neil Johnston
Aerospace Psychology Research Group
Trinity College, Dublin, Ireland
April 2002

Series Foreword

The domain of transportation is important for both practical and theoretical reasons. All of us use transportation systems as operators, passengers, and consumers. From a scientific viewpoint, the transportation domain offers an opportunity to create and test sophisticated models of human behavior and cognitions. This series covers both practical and theoretical aspects of human factors in transportation with an emphasis on their interaction.

The series is intended as a forum for researchers and engineers interested in how people function within transportation systems. All modes of transportation are relevant, and all human factors and ergonomic efforts that have explicit implications for transportation systems fall within the series perview. Analytic efforts are important to link theory and data. The level of analysis can be as small as one person or international in scope. Empirical data can be from a broad range of methodologies, including laboratory research, simulator studies, test tracks, operational tests, field work, design reviews, or surveys. This broad scope is intended to maximize the utility of the series for readers with diverse backgrounds.

I expect the series to be useful for professionals in the disciplines of human factors and ergonomics, transportation engineering, experimental psychology, cognitive science, sociology, and safety engineering. It is intended to appeal to the transportation specialist in industry, government, or academia as well as the researcher in need of a test bed for new ideas about the interface between people and complex systems.

This text on aviation psychology covers a domain that is central to transportation human factors. Many of the principles and practices of human factors originated in aviation psychology work as far back as World War II with the pioneering efforts of Paul Fitts and other historic figures in human engineering. Although the name of the discipline has since morphed into human factors and ergonomics, the system approach to aviation remains and is well illustrated in the present text. I particularly commend the editors for emphasizing the crucial relationship between theory and practice in aviation psychology. Theoretical models of pilot control, perception, decision making, selection, execution and control, attention, mental workload, situational awareness, and cognitive aging are prominently featured throughout the book. Theory and application are linked in each chapter, thus fulfilling a major goal of the series. Forthcoming books in this series will continue this blend of practical and theoretical perspectives.

Barry H. Kantowitz
University of Michigan Transportation Research Institute
Ann Arbor, Michigan

Abbreviations

AA	adaptive aiding
ACFS	Advanced Concept Flight Simulator
ADI	attitude directional indicator
ADM	aeronautical decision making
ADS-B	automatic dependent surveillance-broadcast
AFOQT	Air Force Officer Qualifying Test
AGATE	advanced general aviation transport experiments
AGL	above ground level
AI	attitude indicator
ALPA	Air Line Pilot Association
altitude AGL	altitude above the ground
ANCS	aviate–navigate–communicate–systems management
ANOVA	analysis of variance
APA	American Psychological Association
APAMS	Automated Pilot Aptitude Measurement System
APU	Applied Psychology Unit
AQP	advanced qualification program
ARCS	attention, relevance, confidence, and satisfaction
ASRS	Aviation Safety Reporting System
ASVAB	Armed Services Vocational Aptitude Battery
ATA	adaptive task allocation
ATA-H	ATA from the machine to the human
ATA-M	ATA from the human to the machine
ATC	air traffic control
ATP	airline transport pilot
Auto-GCAS	Automatic Ground Collision Avoidance System
AVOR	angular vestibulo-ocular reflex
BAT	Basic Attributes Test
BFT	basic flying training
CAPSS	Canadian Automated Pilot Selection System
CDI	course deviation indicator
CDTI	cockpit display of traffic information
CDU	control and display unit
CFIT	controlled flight into terrain

CGI	computer-generated imagery
CMAQ	Cockpit Management Attitudes Questionnaire
CNP	central nervous processor
CPL	commercial pilot license
CRM	crew resource management
CRT	cathode ray tube
CTAS	Center Tracon Automation System
CTM	cockpit task management
DA	descent advisor
DECIDE	detect, estimate, choose, identify, do, evaluate
DME	distance measuring equipment
DMS	decision making styles
DMT	defense mechanism test
ECAC	European Civil Aviation Conference
EEG	electroencephalograph
EGPWS	Enhanced Ground Proximity Warning System
EICAS	Engine Indicator and Crew Alerting System
ERP	event-related potentials
ERP	eye reference point
EVA	extravehicular activity
FAA	Federal Aviation Administration
FAR	Federal Aviation Regulation
FFOV	forward field of view
FL	flight level
FMAQ	Flight Management Attitudes Questionnaire
FMC	flight management computer
FMS	flight management system
FO	first officer
FOQA	flight operations quality assurance
FOR	field of regard
FOV	field of view
g	gravity
g	general mental ability, intelligence
G-force	gravity force
G-loading	gravity loading
GA	general aviation
GAT	general aviation trainer
GFOV	geometric field of view
GIF	gravito-inertial force
GIM	global implicit measure
GPS	Global Positioning System
GPWS	Ground Proximity Warning System
GWS	graphical weather service

HMD	helmet-mounted display
HQSF	handling qualities sensitivity function
HTA	hierarchical task analysis
HUD	head-up display
IA^2	Introduction to Aircraft Automation
IFR	instrument flight rules
IJAP	*International Journal of Aviation Psychology*
ILS	instrument landing system
IMC	instrument meteorological conditions
IPISD	interservice procedures for instructional systems development
IPO	input-process-outcome
ISD	instructional systems development
JAA	Joint Aviation Authority
KSAO	knowledge, skill, abilities, and other
LCD	liquid crystal display
LLC	line and line-oriented simulation checklist
LOD	level of detail
LOFT	line-oriented flight training
LQG	linear, quadratic, gaussian
LTM	long-term memory
LTWM	long-term working memory
LVOR	linear vestibulo-ocular reflex
MAT	Multi-Attribute Task
MCP	mode control panel
MDA	minimum descent altitude
MFD	multifunction display
MIDAS	Man-Machine Integrated Design and Analysis System
MIDIS	Microcomputer-Based Flight Decision Training System
MVSRF	Man-Vehicle Systems Research Facility
NAS	National Aerospace System
NASA	National Aeronautics and Space Administration
NATO	North Atlantic Treaty Organization
NDM	naturalistic decision making
NOE	nap-of-the-earth
NTSB	National Transportation Safety Board
OCM	optimal control model
OTTR	otolith-tilt-translation-reinterpretation
OVAR	off-vertical axis rotation
PAN I	Positional Alcohol Nystagmus I
PAN II	reversed PAN I

PC	personal computer
PCATD	personal computer-based aviation training devices
PCSM	pilot candidate selection method
PFT	preliminary flying training
PIO	pilot induced oscillation
PIRIP	risk profile
POC	performance-operating characteristic
PPL	private pilot license
PSD	power spectral density
RA	resolution advisory
R/M	recognition/metacognition model
RMS	root-mean-square
RPD	recognition-primed decision model
RSI	response-stimulus interval
SA	situation (or situational) awareness
SAGAT	Situation Awareness Global Assessment Technique
SD	spatial disorientation
SDT	signal detection theory
SME	subject-matter expert
SMS	space motion sickness
SOP	standard operating procedure
SPARTANS	Simple Portable Aviation Relevant Task-Battery and Answer-Scoring System
SPV	subjective postural vertical
STM	short-term memory
SVV	subjective visual vertical
TCAS	Traffic Alert and Collision Avoidance System
TRACES	Technology in Retrospect and Critical Events in Science
UAV	unmanned air vehicle
URET	user request evaluation tool
VAMP	variable anamorphic motion picture
VFR	visual flight rules
VMC	visual meteorlogical conditions
VOR	vestibulo-ocular reflex
VORs	very-high-frequency omnidirectional range navigational beacons
VR	virtual reality
VSD	vertical situation display
WAD	Workload Assessment Device

1

Introduction to Aviation Psychology

Pamela S. Tsang
Wright State University

Michael A. Vidulich
Air Force Research Laboratory

THE CHANGING ROLE OF THE PILOT

Early Beliefs of the Pilot's Role in Aviation

Heavier-than-air aviation started about 100 years ago with the first remarkable heavier-than-air powered aircraft flight by the Wright brothers in 1903. Many aviation researchers besides the Wright brothers also contributed to the birth of aviation. Otto Lilienthal, Samuel Langley, Octave Chanute, and Glenn Curtiss are just a few of the aviation pioneers that were either predecessors or contemporaries of the Wright brothers. Yet, the Wright brothers' contributions to the birth of modern aviation stand out, not only because of their ultimate success in being the first to demonstrate powered heavier-than-air flight, but also because of the spectacular balance they achieved in combining scientific principles and effective practice in achieving their goal.

For example, the Wright brothers made seminal contributions to the field of aerodynamics in their creation and use of the first wind tunnel to develop the wing shape for their aircraft, the Flyer. Later, they generalized from that knowledge to design propellers of unprecedented effectiveness for the Flyer's propulsion and incorporated the first effective three-axis control system into their 1902 glider (Hallion, 1978; Jakab, 1997).

With all of those signal accomplishments and the compelling image of their dramatic first flight, it is perhaps not surprising that another important contribution of the Wright brothers is often overlooked. The Wright brothers had a much clearer view of the role of the pilot than did many of their contemporaries. Many of the early aviation researchers of the time period believed that the challenging uncertainty of atmospheric conditions required the creation of an inherently stable aircraft that would respond to a human operator's navigational commands, but fly automatically otherwise (Crouch, 1978). In contrast, perhaps due to their background as bicycle mechanics, the Wright brothers saw the pilot of an aircraft as a skilled active controller of an unstable vehicle (Culick & Jex, 1987; Tsang & Vidulich, 1989). This insight guided their use of experimental gliders as a means of not only testing the aerodynamic properties of their designs and control systems, but also as a means for building their own skills as pilots. The central role of skill in their conception of piloting also led the Wright brothers to become pioneers in the field of educating others to fly. It might be overreaching to claim the Wright brothers as the first aviation psychologists, but their keen appreciation for piloting as a skill was certainly a harbinger of things to come.

The Birth of Scientific Aviation Psychology

Roscoe (1980) points out the difficulty in identifying a single founder of scientific aviation psychology, but identifies World War II as a seminal event in the emergence of the field. This is not surprising, given that during the war aircraft developed into weapons platforms that could travel at unprecedented speeds and attempt to deliver bombs with precision from unprecedented altitudes. Controlling these sophisticated machines, navigating them accurately, and using them effectively all required that equipment be developed that was well designed for human use. Also, the fact that many thousands of crew members were required for these aircraft throughout the war encouraged innovative training research. In England, Sir Frederick Bartlett of Cambridge University inspired studies of aviation human factors in support of the war effort at the Applied Psychology Unit. Early research on human vigilance by Norman Mackworth and compatibility between controls and displays by Kenneth Craik were representative of the valuable work conducted by this group (Roscoe, 1997).

Ross McFarland. McFarland's interest in the effects of altitude on mountain dwellers dated from 1928 and led him into scientific investigations in aviation in the 1930s. Probably his best-known work is two of the earliest volumes on human factors in aviation. In the first volume, *Human Factors in Air Transport Design* (1946), McFarland was mostly concerned with the physical variables that should be controlled to meet human requirements and that could be specified as design criteria for aeronautical engineers. Recognizing that not all the problems of flying could be solved by aeronautical engineering, in his second volume, *Human Factors in Air Transportation* (1953), McFarland turned his attention to the integration of the human operator with the equipment. Issues regarding selection and training of flight personnel took center stage. At a time when history first began to witness aging airline pilots, McFarland was concerned with prolonging the useful lives of highly skilled operators. McFarland's approach to understanding ranged from laboratory studies to extensive field observations on aircrews in all parts of the world. McFarland believed that "air transports can be operated safely and efficiently only in so far as the human variables are understood and controlled. The contributions of many specialized scientists are needed to solve these ever-changing problems. In addition, basic research must be continued and the results successfully interpreted and integrated with the practical aspects of airline operations" (1953, p. ix).

Paul Fitts. In the United States, the wartime research on human factors encouraged the May 1945 formation of the Psychology Branch of Aero Medical Laboratory at Wright Field, under the leadership of Paul Fitts (Fitts, 1947; Grether, 1995). Among Paul Fitts' many contributions to aviation psychology were his detailed studies of pilot errors (Fitts & Jones, 1961a, 1961b), pilot eye-scanning behaviors (Fitts, Jones, & Milton, 1950), and the human engineering aspects of air traffic control (Parsons, 1972). However, his contributions extend well beyond the domain of aviation psychology to include producing one of the early, and very influential, taxonomies for function allocation between humans and machines (Fitts, 1962) and evaluation of human manual control characteristics (Fitts, 1954). It is fair to consider Paul Fitts as one of the founders of the entire field of modern human factors, not just aviation psychology.

Alexander Williams. Although Roscoe (1980) was quick to acknowledge the contributions of pioneers such as Bartlett, McFarland, and Fitts, the individual that he nominated as the "Father of Aviation Psychology" was Alexander Williams. After service as a naval aviator during World War II, Williams founded the Aviation Psychology Laboratory at the University of Illinois in 1946. As part of his own research legacy, Williams performed valuable investigations into task decomposition, pilot training, and display and control design (Roscoe, 1980; Williams, 1980). However, even more important than his own individual research contributions, the laboratory founded by Williams has flourished, albeit while undergoing changes in name and directorship. Williams led the laboratory for the first decade following its 1946 founding. Jack Adams and Stanley Roscoe were two of his successors. Roscoe led the lab during a highly productive period in the 1970s (Roscoe, 1980). The current head of the Aviation Research Laboratory at the University of Illinois is Christopher Wickens (author of chap. 5 and 7), and the laboratory's activities remain at the forefront of aviation psychology research.

The Modern Role of the Pilot

The evolution of aviation from the Wright brothers' time until the present day has seen remarkable changes in the capabilities of aircraft. The initial flight by the Wright brothers did not even last a single minute and accomplished no purpose other than to show that powered heavier-than-air flight was possible. Now commercial aircraft flights routinely last many hours and connect cities separated by thousands of miles over entire oceans. Commercial aviation not only provides transportation for people traveling to far-distant lands, but also moves mail and cargo at speeds unattainable any other way. Military aviation has seen even larger increases in capabilities (see, e.g., chap. 2; Shaw, 1985).

As exciting and as important as the increases in aviation capabilities have been, they have not been acquired without affecting the person most responsible for bringing these capabilities to fruition, that is, the pilot. An early pilot received almost all of the vital flight information from his or her own senses. Vision and vestibular functions helped keep the aircraft oriented safely, and navigation was accomplished by sighting landmarks, or even signs, on the ground (e.g., see chap. 3). The pilot had little more than a throttle and a joystick to control the aircraft and often aspired to no more than getting into the air and returning to earth safely. The pilot's world has become much more complex since those early days.

In Fig. 1.1, Wilbur Wright sits in a completely open cockpit, illustrating the simplicity enjoyed by early pilots. All of the information used to control his flight was gained through direct observation of the world. The simple and few controls available to him were connected directly to the aircraft control surfaces with no intermediary.

Buck (1994) details many of the technological changes that have confronted pilots over the course of his own flying career that spanned most of the 20th century. Buck noted the appealing simplicity of early flight. Here are his memories of a 1931 flight in a biplane Pitcairn Mailwing aircraft (23 years after the photo of Wilbur Wright in Fig. 1.1 was taken):

> Imagine flying across New York City through the northeast corridor with no traffic, no ATC, no two-way radio, not a thing to think about except those key basics: fly the airplane, navigate, and avoid the terrain. It was a beautiful, simple life. (p. 8)

Continuing his flying career through World War II, through the formative years of modern commercial air travel, and up to current times, Buck outlined the increasing list of concerns and issues that have been added to the pilot's burden. In many cases, items added to increase safety or effectiveness became potential problems that required additional effort to monitor and control. The same proliferation of additional systems to be controlled confronted the military pilot, along with changes in weapons technology from first controlling the settings for the

FIG. 1.1 The simplicity of early flight. Wilbur Wright on a triumphal tour of Europe in August 1908. Sitting at the controls of the Wright 1907 Flyer at Les Hunaudieres race course near Le Mans. (Courtesy of Special Collections and Archives, Wright State University)

increasingly sophisticated sighting systems for guns and progressing to controlling the launching of air-to-air missiles (Coombs, 1999).

Until the 1960s, the additional information presented to the pilot usually took the form of another single-purpose instrument (Coombs, 1990). Fig. 1.2 illustrates a cockpit from this time period. The numerous single-purpose indicators could exert a serious visual scanning and cognitive integration load on the pilot (see chap. 5). Additionally, as aircraft became increasingly complex and the amount of information that needed to be presented to the pilot increased, the finite "real estate" of the cockpit became a limiting factor. As Coombs put it (1990), "A point in evolution was reached in which the number of pointers, numeral counters and flags could no longer be increased or their display characteristics improved" (p. 12).

The breakthrough in the appearance of the cockpit occurred during the 1960s when cathode ray tube (CRT) displays became practical for use in the cockpit (Coombs, 1990). Because the appearance of the display was no longer limited by

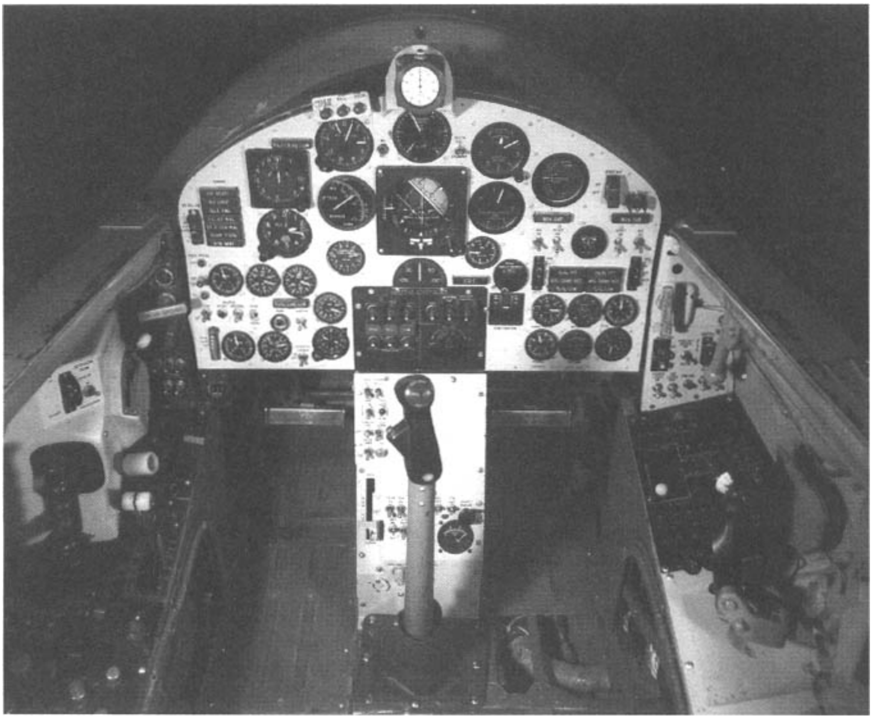


FIG. 1.2 Typical cockpit design of the early 1960s, as illustrated by the X-15. The X-15 research rocket aircraft provided much-needed information on high-speed flight for NASA's space program. The X-15 cockpit shows the use of individual instruments to display data to the pilot. (Courtesy of NASA)

the physical constraints of moving the electromechanical indicator, CRTs allowed innovative display formats to be used. And, by allowing different displays to appear on the same CRT at different times, CRTs were a great boon for alleviating the cockpit real estate problem. CRT technology was followed by liquid crystal displays (LCD) that also allowed flexible multifunction formats.

The prominent role of multifunction displays in the modern cockpit is well illustrated by the Boeing 777 cockpit shown in Fig. 1.3. The change from single instruments and gauges to flexible multifunction displays makes the modern cockpit look much different than earlier cockpits (such as that illustrated in Fig. 1.2). However, much more has changed than just the appearance of the cockpit. In addition to the changes in display technology, the 1960s ushered in the use of computerized automation to assist pilots. For example, the Boeing 777 computer systems incorporate more than 2.6 million lines of software code to support the autopilot, flight management, navigation, and maintenance functions (Norris & Wagner, 1996).

FIG. 1.3 The Boeing 777–300 flight deck: The newest member of the 777 family is a large, modern commercial air carrier. The 777 flight deck illustrates the use of large multipurpose displays to efficiently convey a great deal of information to the crew. (Courtesy of the Boeing Company)

Thus, the current commercial and military pilot has become increasingly removed from direct contact with the aircraft control surfaces. More and more of the tasks require that the pilot work cooperatively, not only with other crew members, but also with advanced computerized technologies (Buck, 1994; Coombs, 1990, 1999). Unfortunately, these advanced computerized technologies often behave in surprising or inexplicable ways to the human pilot (Sarter & Woods, 1992, 1994). On the other hand, researchers (e.g., Weiner, 1993) have pointed out that automation often has positive effects, even on the pilot's cognitive processing, by enabling effective responses in emergencies that would not be possible without it.

Nevertheless, Buck (1994) closed his book arguing that more consideration needs to be paid to the pilot's role:

> Our plea, then, is to develop and then implement real ways to reduce rather than add to the pilot's burden, to simplify the pilot's job rather than complicate it. To respect, finally, that pilot judgment will always be needed—and to make room for it. (p. 233)

Visualizing the Future Pilot

Undoubtedly, the role of the pilot in commercial and military aviation will continue to be affected by the trend toward more highly automated systems. It is hoped that as these systems become more advanced, they will meet Buck's plea to reduce rather than to expand the pilot's burden. Some researchers believe that this happy result will occur as the automated systems become intelligent enough to become "electronic crew members" (see, e.g., Reising, Taylor, & Onken, 1999) and become more "aware" of the actual state of the pilot they are attempting to aid (e.g., see Taylor, Howells, & Watson, 2000; see also chaps. 4 and 9).

In a broader context, Fallows (2001a, 2001b) presents another intriguing vision of the future of aviation. Examining the increasing bottlenecks and delays inherent in the existing airline industry, Fallows proposed that a simple scaling-up of the existing system with more planes and more runways at existing airports would not be a practical or economically viable approach to keep pace with the projected increases in airline travel. Fallows made a compelling argument that the increased reliability of aircraft mechanical systems combined with innovative research on cockpit interfaces will not only revitalize general aviation, but will also lead to the emergence of a much more extensive small aircraft "taxi" service.

In the current context, it is important to emphasize the role that human factors is expected to assume in the development of the expanded air system. Fallows (2001a, 2001b) points out that current research, such as that performed by the National Aeronautics and Space Administration's (NASA) Advanced General Aviation Transport Experiments (AGATE) alliance, will decrease the difficulty of piloting and increase flight safety for a new generation of more user-friendly aircraft. NASA is aggressively pursuing the goal of making advanced cockpit technologies effective and affordable to even general aviation pilots. These technologies include highway-in-the-sky displays, head-mounted displays (Fiorino, 2001), and synthetic vision systems that use advanced sensors to present a view of the world to the pilot during degraded visual conditions (Wynbrandt, 2001).

Fallows (2001a, 2001b) presented his vision of aviation's future before the tragic September 11, 2001, terrorist attacks on the World Trade Center and the Pentagon. The ensuing turmoil, security increases, and economic downturn that the airline industry experienced following the attacks will, at least, slow movement toward such an open expansion of the U.S. and international aviation systems. However, it seems inevitable that in the long run civilization will continue its development of increased mobility for people and that the aviation system will change in ways to accommodate that increase. To this end, understanding the human pilot and building systems that best accommodate the human's cognitive strengths while supporting human frailties will remain a vital component of making those systems effective and safe.

THE ROLES OF BASIC AND APPLIED RESEARCH IN AVIATION PSYCHOLOGY

Basic and Applied Research in Meeting Future Needs

A major organizing principle of this book is the belief that a viable practice of aviation psychology must be based on a solid theoretical foundation. Maintaining the balance of basic and applied work within the field has always been important in both aviation psychology and in the broader domain of engineering psychology. This challenge was forthrightly faced 30 years ago by Jack Adams (Adams, 1972) in his 1971 Presidential Address to the Society of Engineering Psychologists, Division 21 of the American Psychological Society (APA). In the opening of his address, Adams stated, "Our research efforts have been and are insufficient. The future of engineering psychology is in jeopardy unless we examine realistically the state of our knowledge and ask what we must do to strengthen it" (p. 615). Adams contrasted Division 21's basic research activities with that of the other applied divisions of the APA (such as clinical psychology and educational psychology) and found Division 21 to be wanting. Adams found in his review several examples of engineering psychology research activities that had promising starts in World War II, but had failed to continue to a satisfactory conclusion. Interestingly, many of these examples involved early aviation psychology research on the design of aviation displays (e.g., attitude displays, circular versus linear displays, pictorial navigation displays, and contact analog displays for vehicular control).

Adams (1972) also considered the outcome of two major studies of the precursors to successful system designs as a means of contrasting the relative merit of basic and applied research. Project Hindsight, conducted by the Department of Defense, examined 20 successful and important military systems to determine what research and development innovations preceded them. The precursors were tracked back about 20 years, and 710 related research and development innovations were identified. The results strongly supported the contribution of applied research. The majority of the precursor innovations identified within Project Hindsight were developed in an applied setting in which the researcher was attempting to address a known deficiency rather than simply to extend domain knowledge. However, Adams pointed out that the research was most often done in support of another system development process, and the median timing was 9 years prior to application of the innovation. In other words, good research, including applied research, can have implications well beyond its current setting.

An even more interesting picture emerged when the 20-year window preceding innovations was expanded. A second study reviewed by Adams (1972) was conducted by the Illinois Institute of Technology and called Technology in Retrospect and Critical Events in Science (TRACES). In examining the essential precursors to five important technologies, 341 precursors were identified as far back as 50 years prior to the current technology. Seventy percent of the precursors were identified as originating in university basic research, and the most common time window was 20 to 30 years prior to the development of the ultimate system.

Adams (1972) concluded that engineering psychology must be more aggressive in examining its own knowledge store and seek to develop a stronger basis for science and its applications. Although applied research answering immediate questions would certainly be vital for the field, Adams (1972) suggested that:

> Furthermore, unfettered basic scientists, going where their imaginations take them, can give applied investigators a vision they otherwise would not have. I cannot believe that applied scientists of the 1930s and 1940s who were concerned with the efficiency of explosives would have ever invented the atomic bomb. (p. 621)

The Role of Basic Research and Theory in Aviation Psychology Practice

In a review, Gopher and Kimchi (1989) considered the implications of the increasing pace of technological changes on the field of engineering psychology in general. The rapidly increasing power of microcomputers and their increasing incorporation within almost every type of human-machine system (especially aircraft) was seen to be a fundamental problem for engineering psychology. It was not seen to be cost effective to engage in long-term applied research for systems that would only last for short periods. As an analogy, Gopher and Kimchi likened the situation confronting engineering psychology researchers to a controller tracking an input function exceeding its point-to-point tracking capabilities. The best response of the controller is to give up attempting to react to every momentary deviation and to focus instead on: (a) tracking any higher order, slow-moving changes within the input function and (b) attempting to predict future inputs. Gopher and Kimchi translated this analogy to the domain of engineering psychology:

> . . . the analogy emphasizes the role of theoretical models in practical work. Only with such models can we generate principles and predict the future. If there existed only a limited set of slow-moving technologies, strict empirical approaches could suffice. (p. 432)

Along the same vein, Kantowitz (1992) identified five major advantages that theory provided the real-world practitioner: (a) Theory can provide accurate and sensible extrapolation to new situations, (b) theory can be the basis for precise predictions of system performance before a system is built, (c) theory can encourage efficient generalization across a range of practical problems (i.e., theory can keep researchers from constantly reinventing the wheel), (d) theory can provide a normative baseline for judging human and system performance to determine whether additional effort might produce significant improvements, and (e) theory is the best practical tool.

The last point best summarizes Kantowitz's (1992) and Gopher and Kimchi's (1989) viewpoints and the organizing principle behind the present volume. As in the larger domain of engineering psychology, the pace of technological changes in aviation has long been too rapid to allow a totally reactive applied research strategy to succeed. The only rational option, then, is to make thorough use of basic research and theories as the foundation of the field of aviation psychology. There will be ample opportunity and compelling need for focused applied research to optimize the application of theory to emerging technologies, but this research will have its best chance to succeed if it makes good use of the theory for guidance.

A visionary, Donald Broadbent was one of the most important figures in experimental and applied psychology during the 20th century (Moray, 1995). As a student, he was mentored by Sir Frederick Bartlett and eventually became head of Cambridge's prestigious Applied Psychology Unit. Being a renowned theoretician himself, it is not surprising that Broadbent held the importance of theory to applications with the same regard as Gopher and Kimchi (1989) and Kantowitz (1992). In addition, Broadbent forcefully advocated the role of applied work in inspiring good theory. Results of applied research, in addition to being practically useful, should also provide tests and expansion of the underlying theory. In summarizing his views after a careful consideration of the role of applied problems in advancing psychological theory, he wrote, "applied psychology is the best basis for a genuine theory of human nature" (Broadbent, 1971, p. 29). To illustrate the point, Broadbent pointed to two attentional mechanisms that had been discovered in applied work and then became prominent in his attentional theories:

> Such mechanisms might be overlooked by purely theoretical psychologists, who can ignore the complex nature of most real-life situations. Once found, these principles are of use in understanding many other situations as well as those that gave rise to them; that is, they are "theoretical" in the best sense. (1971, p. 30)

This volume was inspired by the same beliefs expressed by Donald Broadbent, namely, that theories and applications are not two distinct goals of aviation psychology, but two essential facets of progress in any healthy science. Just as good psychological theories will help guide applications to aid the pilot, the challenging applications inherent in aviation will provide a fertile ground to grow robust theories.

PREVIEW OF THE CHAPTERS

Although the chapters are arranged by important topics in aviation psychology, readers will find pertinent psychological principles, their associated methodologies, and related empirical findings discussed throughout the book. The book adopts a psychological perspective toward understanding the demands on the pilot. Following the arguments presented earlier, we hold that systematic investigations with the rigor of scientific methods would be the most fruitful approach. This approach should yield principles and methodologies that would contribute to the understanding of human behavior in general and to enhancing performance in a variety of systems and settings beyond that of aviation. For example, a sound display principle would apply in the cockpit of an aircraft, a spacecraft, an air traffic control's console, or an automobile dashboard, as well as an office computer. The book also adopts the view that the understanding of human behavior can be greatly informed by applied problems. Issues related to the enhancment of pilot performance and to the improvment of system efficiency and safety should drive the selection of topics to study. For example, one important consideration that spans across the chapters is the impact of the ever-changing technology on the pilot's task. We believe the juxtaposition of theories and applications in each chapter will help us achieve the goal of attaining a better understanding of the pilot–aircraft system and being in a better position to contribute to the extant knowledge.

The chapter by Ralph and Lyn Haber, "Perception and Attention in Low-Altitude High-Speed Flight" (chap. 2), introduces some flying basics. The detailed analysis of low-altitude flight in military aviation shows the intrinsically unforgiving nature of aviation and the rich interplay of perceptual and attentional abilities and skills required of the pilot. The detailed account of the highly specialized operational tasks from a psychological viewpoint elucidates the role of psychologists in aviation. Haber and Haber present some of the most pertinent principles of psychology to flight but also illustrate the limitations of current theories. Appreciating the limitations of current theories is, of course, a necessary step towards advancing theories. This chapter exemplifies the fruitfulness of psychologists working hand in hand with operational personnel, applying basic knowledge to the understanding of operational demands, and validating theoretical understandings through detailed analysis of the operational performance. Haber and Haber's discussion foreshadows several major topics covered in the ensuing chapters.

Three chapters cooperatively cover a topic of the earliest concerns of flight—pilot control. Continuous vehicular control is often the pilot's main activity whenever the aircraft cannot be left to an autopilot. The demands of pilot control are illustrated by the examples of combat maneuvers deftly sketched by Haber and Haber. In chapter 8, Hess presents formal quantitative pilot control models. For those with less of a quantitative background, Wickens provides a more intuitive description of pilot control models in chapter 7. The models presented by Hess are mathematical constructs that can be used in descriptive or predictive fashion. The models can be used to describe or explain results observed from flight tests or simulation runs, contributing to the understanding of human pilot behavior. The pilot models also can be used to predict pilot/aircraft performance and handling qualities, thus contributing to improved aircraft designs. The advantages of adopting psychological constructs developed by psychologists in conjunction with the powerful analytical techniques used by engineers are amply evident in this chapter. Hess believes this to be an efficient approach to identifying aids that could be provided to the operator and determining the appropriate roles of humans and machines in pilot control.

Several chapters expand on the perceptual and attentional issues facing the pilots that Haber and Haber related to piloting. As discussed in Young's (chap. 3), Hess's (chap. 8), and Kaiser and Schroeder's (chap. 12) chapters, perception is accomplished through not just the visual system, but also the auditory, proprioceptive, and vestibular systems. Of note is that these authors emphasize the importance of the integration of the signals from the various sensory systems in contributing to spatial orientation, pilot control, and motion perception.

Similarly, with regard to the attentional issues, instead of focusing on isolated, single-task performance, Vidulich (chap. 4), Wickens (chap. 7), and Tsang (chap. 14) consider attentional management as a higher order cognitive skill with subcomponents that involve the executive control of limited resources. Vidulich presents the concepts of mental workload and situation awareness that are now frequently used to characterize the impact of complex aviation tasks on the pilot's information processing system. Wickens discusses how pilots cope with the temporal demands of multiple tasks (Cockpit Task Management, CTM)—a critical issue in the cockpit in which checklist activities might easily be time-shared with, or interrupted by, other tasks. Tsang focuses on two components of the executive control—attention switching and attention sharing—and how age and expertise might affect this control.

The impressive maneuver capability of modern aircraft demonstrated in Haber and Haber's chapter reflects the increasing sophistication of aviation technology that has far-reaching implications on an array of issues covered in the book. For one, it points to the opportunity and need for automation to support pilot control. But as researchers have long recognized (notably, Wiener & Curry, 1980) and as Parasuraman and Byrne have discussed in the present volume (chap. 9), although automation is largely helpful, enabling operations that would otherwise be impossible, it also has placed an additional burden on the pilot. With the advent of increasing automation, the role of the pilot shifts from primarily a manual controller of focused, isolated tasks to a supervisory controller overseeing and managing several subsystems concurrently. This has important implications on the level of psychological processes that require understanding, and new psychological concerns emerge. For example, concepts like mental workload and situation awareness (chap. 4) are relatively new to the psychological literature. These concepts actually originated from the operational personnel who felt a need for new vocabulary to describe the demands and challenges that they face. In addition to providing a thorough overview of the issues associated with the use of automation within the cockpit, Parasuraman and Byrne and Vidulich propose that future automation might take advantage of monitoring the human's mental state in order to act more adaptively and intelligently.

Although automation moves the pilot further and further from direct control, the pilot still requires information to keep abreast of the state of the aircraft in order to aviate, navigate, communicate, and manage all the subsystems. In chapter 5, Wickens advocates the use of psychological principles to shape the presentation of information. A well-designed display should seem "intuitive" to the pilot. The flexibility of information formats afforded by modern display technology provides great opportunity to achieve compatibility between display format and the pilot mental information processing.

The additional information afforded by technology (such as real-time traffic information) can be enormously helpful for many decision-making tasks. But additional sources of information, along with all their inherent uncertainty, could also increase the complexity of decision making. Further, technology can now effect a decision with a push of a button or a simple voice command that could produce quick and far-reaching consequences. In chapter 6, O'Hare argues that the understanding of human decision making is one of the primary issues confronting aviation psychology. He presents both normative and descriptive models of human decision making but found the current attempts to provide decision-making training to be not particularly effective. O'Hare advocates for continual development of theoretical understanding and the use of a better theory-based tool for more effective interventions.

The challenges inherent in the increasing technological capabilities and the anticipated increasing volume of air travel around the globe call for new consideration on pilot selection and training. These issues are covered in chapters 10 and 11, respectively. The early disastrous results of training unselected individuals for flying during the first years of World War I prompted intensive study of pilot selection across the globe (Armstrong, 1939). It also soon became clear that physical fitness alone was not sufficient to guarantee success in aviation. Tests of emotional stability, personality, and cognitive tests of memory, attention, and spatial ability were therefore implemented. In the present volume, Carretta and Ree (chap. 10) discuss the complexities of trying to identify individuals who are likely to succeed as a pilot. State-of-the art selection batteries for commercial and military selection from around the world are presented.

Though not covered extensively, Carretta and Ree rightly raise the issue of considering the advantages of selection methods to be able to predict training and job performance for members of both genders and members of different ethnic/racial groups. In 1934, Helen Richey was the first woman pilot to be hired by a regularly scheduled airline. However, the Federal Bureau of Air Commerce forbade her to fly in bad weather, and the all-male pilot's union denied her membership (Thornberg, 2000). In was not until 1973 that a U.S. airline would hire a second woman pilot (see Fig. 1.4). As of 1994, female airline pilots constituted 2.3% and African American airline pilots constituted 1.2% of the airline pilots' population (Hansen & Oster, 1997). Hansen and Oster (1997) urge a concerted effort to increase diversity in the aviation workforce to maximize human capital.

Along the same vein, to capitalize on the skill and experience of older pilots, there are ongoing fervent debates surrounding the FAA Age 60 Rule. This regulation prohibits pilots over the age of 60 to be the pilot-in-command of air carriers and commuter and air taxi operations that include 10- to 30-seat aircraft. Tsang (chap. 14) presents the debates on the potential benefits and compromises in safety with the possible revision of the Age 60 Rule. A scientific, objective approach that could contribute to the current debates is proposed.

Effective selection methods minimize but do not obviate the need for training. In chapter 11, Patrick provides an overview of the design, implementation, and evaluation of a training program for individuals and teams. In this endeavor, Patrick emphasizes equally the reliance on general principles found in the literature and on more specific lessons learned from training studies in aviation. Patrick considers the strengths and weaknesses of the traditional Instructional System Development model within the context of training of an individual pilot, as well as that of increasing automation and the need for crew coordination.

Another implication of the increasing capability made possible by technology is the need for additional personnel to control and manage the aircraft systems. Effective information flow among crew members becomes an important factor toward maximizing performance and safety. In chapter 13, Sherman reviews the impact of the demands of processing additional information as well as those of increased social interaction among crew members. Sherman shows how Crew Resource Management (CRM) emerged as an approach for improving team communication and coordination. Whereas technology had gradually transformed a single-pilot cockpit to a three-person cockpit for air carriers (with a pilot-in-command, a copilot, and a

FIG. 1.4 Bonnie Tiburzi, the second woman pilot hired by a U.S. air carrier and the first to be hired by a major airline. (Courtesy of the Ninety-Nines, Museum of Women Pilots)

flight engineer), the newer, more automated cockpits experience a reduction in crew size, with the flight engineer being eliminated from most cockpits. As discussed by Sherman, this turn of events does not reduce the need to understand teamwork. Rather, team communication and coordination research needs to be conducted to incorporate the electronic crew members.

Because flight simulation is frequently used for training and for the evaluation of training, the two topics are intricately related (e.g., What should be simulated in order to maximize transfer of training?). In addition, flight simulators can be used for developing and testing aircraft models (chap. 12) and mathematical constructs of pilot control such as those discussed by Hess (chap. 8). The many advantages of the use of simulation were recognized early. The first simulators were naturally very crude by today's standards, but the regimes of flight that could be reasonably emulated expanded with the present computer processing and video presentation capabilities. Although the degree of physical realism that can be achieved today is arresting, the most powerful computer in the world still cannot duplicate the world. The mere use of a realistic setting does not mean that a study is valid. Any number of unintended factors could render it impossible to draw any inferences from the results with confidence. Instead of aiming for surface realism, it is utterly important to first identify the critical variables that support piloting. This is one aspect in which guidance by a solid theoretical foundation rather than by technical feasibility is especially needed (see also chap. 11).

Several chapters also offer tutorials on some of the most common analytical methods used in aviation psychology. In chapter 4, Vidulich provides a tutorial on important techniques used for assessing mental workload and situation awareness. In chapter 7, Wickens presents a tutorial on control theory that would be most helpful for those who would need some introductory background to appreciate the more quantitative treatment presented by Hess in chapter 8. In chapter 10, Carretta and Ree provide an overview of the validation process, specific analytic strategies, and cautionary notes on the many potential pitfalls in drawing conclusions from improperly conducted analysis. The invaluable lessons found in this chapter should be applicable in a variety of settings. In chapter 11, Patrick presents the general steps taken in conducting a training program. In chapter 14, Tsang presents the common approaches to, as well as methodological challenges in, assessing age effects on pilot performance.

Finally, the treatment of aviation errors and accidents are more explicit in some chapters (e.g., chaps. 2, 3, 6, 9, 11, 13, and 14) than in others. But all chapters address issues that, through training (e.g., chaps. 2, 3, 11, and 13), by design (e.g., chaps. 5, 7, 9, and 12), by our ability to predict pilot performance (e.g., chaps. 6 and 8), or by capitalizing on pilots' skill and experience (e.g., chaps. 4, 10, and 14), aim at reducing errors and minimizing accidents, while enhancing safety and efficiency.

To conclude, the rapid metamorphosis of flight in a mere 100 years is nothing short of breathtaking. The early paths that pioneer aviation and engineering psychologists have set out for us appear to be good ones. The common approach among them is the need to continue basic laboratory research and bring it to bear on applied issues. But as Broadbent (1990) put it, "the world has features that current theory cannot handle" (p. 237). Consequently, basic research also should be driven by some important practical problems, and applied studies should be conducted as test of the theory. Further, the findings of such studies should be used to modify the underlying theory. The future of aviation psychology does not lie in comparing the merits of various subsystems. Rather, it lies in understanding the underlying principles in design alternatives for intelligent pilot–aircraft systems. Toward this end, as the pilot's task becomes more the managing of complex systems, the understanding of the performance of highly simplified tasks and processing isolated signals would not suffice. The information processing that typifies piloting requires a high level of comprehension, dynamic decision making, executive control, organization, and integration. Advancing the theoretical understanding of the pilot behavior in the complex, demanding aviation environment will require research to be conducted in an environment sufficiently rich to allow the elicitation of behavior that would be representative of today's piloting. This is the case for laboratory, simulation, or field experiments. But for this process to move forward, institutional and government recognition of, support for, and commitment to equipment and resources needs are necessary.

REFERENCES

Adams, J. A. (1972). Research and the future of engineering psychology. *American Psychologist, 27,* 615–622.

Armstrong, H. G. (1939). *Principles and practice of aviation medicine.* Baltimore: Williams & Wilkins.

Broadbent, D. (1971). Relation between theory and application in psychology. In P. B. Warr (Ed.), *Psychology at work* (pp. 15–30). Harmondsworth, England: Penguin.

Broadbent, D. (1990). A problem looking for solution. *Psychological Science, 1,* 235–239.

Buck, R. N. (1994). *The pilot's burden: Flight safety and the roots of pilot error.* Ames: Iowa State University Press.

Coombs, L. F. E. (1990). *The aircraft cockpit: From stick-and-string to fly-by-wire.* Derby, England: Patrick Stephens Limited.

Coombs, L. F. E. (1999). *Fighting cockpits 1914–2000: Design and development of military aircraft cockpits.* Shrewsbury, England: MBI Publishing.

Crouch, T. D. (1978). Engineers and the airplane. In R. P. Hallion (Ed.), *The Wright brothers: Heirs of Prometheus* (pp. 3–19). Washington, DC: Smithsonian Institute.

Culick, F. E. C., & Jex, H. R. (1987). Aerodynamics, stability, and control of the 1903 Wright Flyer. In H. S. Wolko (Ed.), *The Wright Flyer: An engineering perspective* (pp. 19–43). Washington, DC: Smithsonian Institute.

Fallows, J. (2001a). *Free flight: From airline hell to a new age of travel.* New York: Public Affairs.

Fallows, J. (2001b, June). Freedom of the skies. *The Atlantic, 287*(6), 37–49.

Fiorino, F. (2001, August 13). Tech trickle-down enhances GA safety. *Aviation Week & Space Technology, 155*(7), 52.

Fitts, P. M. (1947). Psychological research on equipment design in the AAF. *American Psychologist, 2,* 93–98.

Fitts, P. M. (1954). The information capacity of the human motor system in controlling the amplitude of movement. *Journal of Experimental Psychology, 47,* 381–391.

Fitts, P. M. (1962). Functions of men in complex systems. *Aerospace Engineering, 21,* 34–39.

Fitts, P. M., & Jones R. E. (1961a). Analysis of factors contributing to 460 "pilot-error" experiences in operating aircraft controls. In H. W. Sinaiko (Ed.), *Selected papers on human factors in the design and use of control systems* (pp. 332–358). New York: Dover.

Fitts, P. M., & Jones R. E. (1961b). Psychological aspects of instrument display: I—Analysis of 270 "pilot error" experiences in reading and interpreting aircraft instruments. In H. W. Sinaiko (Ed.), *Selected papers on human factors in the design and use of control systems* (pp. 359–396). New York: Dover.

Fitts, P. M., Jones, R. E., & Milton, J. L. (1950, February). Eye movements of aircraft pilots during instrument landing approaches. *Aeronautical Engineering Review, 9*(2), 24–29.

Gopher, D., & Kimchi, R. (1989). Engineering psychology. *Annual Review of Psychology, 40,* 431–455.

Grether, W. F. (1995). Human engineering: The first 40 years, 1945–1984. In R. J. Green, H. C. Self, & T. S. Ellifritt (Eds.), *50 years of human engineering* (pp. 1-9–1-17). Wright-Patterson Air Force Base, OH: Crew Systems Directorate.

Hallion, R. P. (1978). The Wright brothers: A pictorial essay. In R. P. Hallion (Ed.), *The Wright brothers: Heirs of Prometheus* (pp. 57–100). Washington, DC: Smithsonian Institute.

Hansen, J. S., & Oster, C. V., Jr. (Eds.). (1997). *Taking flight.* Washington, DC: National Academy Press.

Jakab, P. L. (1997). *Visions of a flying machine: The Wright brothers and the process of invention.* Washington, DC: Smithsonian Institute.

Kantowitz, B. H. (1992). Selecting measures for human factors research. *Human Factors, 34,* 387–398.

McFarland, R. A. (1946). *Human factors in air transport design.* New York: McGraw-Hill.

McFarland, R. A. (1953). *Human factors in air transportation: Occupational health and safety.* New York: McGraw-Hill.

Moray, N. (1995). Donald E. Broadbent: 1926–1993. *American Journal of Psychology, 108,* 117–121.

Norris, G., & Wagner, M. (1996). *Boeing 777.* Osceola, WI: Motorbooks International.

Parsons, H. I. (1972). *Man-machine system experiments.* Baltimore: Johns Hopkins University Press.

Reising, J., Taylor, R., & Onken, R. (1999). *The human-computer crew: The right stuff? Proceedings of the 4th Joint GAF/RAF/USAF Workshop on Human-Computer Teamwork* (Tech. Rep. No. AFRL-HE-WP-TR-1999–0235). Wright-Patterson Air Force Base, OH: Air Force Research Laboratory.

Roscoe, S. N. (1980). Preface: Roots of aviation psychology. In S. N. Roscoe (Ed.), *Aviation psychology* (pp. xi–xiv). Ames: Iowa State University Press.

Roscoe, S. N. (1997). *The adolescence of engineering psychology: Vol. 1. Human Factors History Monograph Series.* Santa Monica, CA: Human Factors and Ergonomics Society.

Sarter, N. B., & Woods, D. D. (1992). Pilot interaction with cockpit automation: Operational experiences with the flight management system. *International Journal of Aviation Psychology, 2,* 303–321.

Sarter, N. B., & Woods, D. D. (1994). Pilot interaction with automation II: An experimental study of pilots' model and awareness of the flight management system. *International Journal of Aviation Psychology, 4,* 1–28.

Shaw, R. L. (1985). *Fighter combat: Tactics and maneuvering.* Annapolis, MD: Naval Institute Press.

Taylor, R. M., Howells, H., & Watson, D. (2000). The cognitive cockpit: Operational requirement and technical challenge. In P. T. McCabe, M. A. Hanson, & S. A. Robertson (Eds.), *Contemporary ergonomics 2000* (pp. 55–59). London: Taylor & Francis.

Thornberg, H. B. (2000). Women in aviation. In T. Brady (Ed.), *The American aviation experience: A history* (pp. 367–412). Carbondale: Southern Illinois University.

Tsang, P. S., & Vidulich, M. A. (1989). Cognitive demands of automation in aviation. In R. S. Jensen (Ed.), *Aviation psychology* (pp. 66–95). Aldershot, England: Gower.

Wiener, E. L. (1993). Life in the second decade of the glass cockpit. In *Proceedings of the Seventh International Symposium on Aviation Psychology* (Vol. 1, pp. 1–7). Columbus: The Ohio State University.

Wiener, E. L., & Curry, R. E. (1980). Flight-deck automation: Promises and problems. *Ergonomics, 23,* 995–1011.

Williams, A. C. (1980). Discrimination and manipulation in flight. In S. N. Roscoe (Ed.), *Aviation psychology* (pp. 11–32). Ames: Iowa State University Press.

Wynbrandt, J. (2001, Spring). Seeing the flightpath to the future: Synthetic vision and heads-up displays are on the way to a cockpit near you. *Pilot Journal, 2*(2), 30–34, 94.

2

Perception and Attention During Low-Altitude High-Speed Flight*

Ralph Norman Haber
Lyn Haber
University of California at Santa Cruz

In this chapter, we undertake a perceptual and attentional analysis of exceedingly complex performance: military low-altitude flight. This performance comprises a constellation of tasks that represent the very edge of human perceptual and attentional capabilities. Our analysis extends the concept of automatic and controlled attention as it has evolved from primarily verbal and semantic tasks to automatic and controlled perceptual processes. This extension is critical because performing on the edge, where death is the presumptive consequence of every mistake, creates a massive conundrum: many of the automatic perceptual processes available to pilots often produce information that is sometimes misleading or simply wrong. As a result, at precisely those moments when perceptual and attentional demands on the pilot are most extreme, he is forced to switch from automatic to focused processes. Further, both perceptual and performance tasks must be prioritized by their importance (defined by likelihood of dying), the duration of the task itself, and the duration of the time interval before the task must be performed again. A major component in every prioritization is whether automatic processes have to be abandoned in favor of focused ones. Just considering this possibility requires focused attention.

---

*A brief note about language. We use the pronouns he and his exclusively when referring to a pilot of combat jet aircraft, because at that time there were no women flying jet fighters in low-altitude arenas.

Military pilots, maneuvering their jet fighters at high speed during low-altitude flight, must also complete their mission tasking and avoid threats. Low-altitude flying provides a laboratory for the analysis of perceptual and attentional processes under conditions where efficiency must be maximized, perception controls and is controlled by performance, and prioritization of tasking determines survival. Typical velocities are just up to the speed of sound, between 600 and 1,000 feet per second. A fighter plane can roll 360 degrees around its axis of travel in little more than a second, enter a turn at a 90-degree angle of bank from level flight in even less time, and complete a U-turn in less than half the time it can be done in a sports car. When these maneuvers are performed near the ground, they can produce angular velocities at the pilot's eyes exceeding 500 degrees per second. They also require the ability to perceive and comprehend objects and terrain at distances of 5,000 to 10,000 feet.

Performing these maneuvers at low altitude places a unique constraint on the pilot. Whatever his reason for flying low, his most important task at all times is to avoid hitting the ground. Successful ground avoidance requires that the pilot's direct and continuous visual attention be focused on observation of the ground. He must perceive the ground, perceive his location relative to the ground, and predict where he will be in relation to the ground during and at the completion of every maneuver.

By definition, a pilot enters the low-altitude environment whenever his primary task at the moment is to avoid hitting the ground (Miller, 1983). Thus, the definition of the low-altitude environment requires knowing the pilot's tasks rather than his absolute elevation over the terrain. Given the speed and maneuverability of modern jet fighters, for some maneuvers low altitude may extend to 5,000 or even 10,000 feet above ground level. For example, a "Split S" maneuver, in which the pilot reverses direction by diving under in order to come up and behind an approaching plane, requires the pilot to first roll inverted, then dive upside down toward the ground in a 180-degree half loop, so that he can pull out into level flight traveling in the opposite direction, though much closer to the ground. At normal maneuvering speeds, most fighters require a vertical diameter of about one mile for their diving loop. Therefore, when planning to begin this maneuver, even at a "safe" altitude of 5,000 feet above ground level, the pilot must be concerned with his ground clearance—he is flying at that moment in the low-altitude environment.

Flying near the ground (except when preparing to land) rarely occurs in general or commercial aviation, and heavy maneuvering near the ground is usually explicitly prohibited by regulation. However, in military aviation, flying near the ground is common for reasons of weather, protection, and mission.

Weather drives pilots low. Because the priorities of military missions take precedence over the momentary weather, a fighter pilot looking for a target he must detect visually may be forced to fly below the bottoms of the clouds, even if that means flying very close to the ground. The need for protection drives pilots low. A jet fighter is more difficult to detect by pilots of other planes, ground observers, or electronic surveillance technology when flying very close to the ground. Even if detected, it is much more difficult to successfully attack a jet flying very close to the ground, especially with heat-sensitive missiles. The mission also drives pilots low. Jet fighter pilots have to go where their targets are located, either to pursue an enemy plane that goes low or to attack a ground target.

In the four sections that follow, we analyze the perceptual and attentional components of avoiding collision with the ground while flying fast and low. In the first section, we describe the aerodynamics of low-altitude flight maneuvers. In the second, we examine the objective information in the physical world that can inform the pilot about his ground clearance. In the third, we explore how those sources of information, singly and in combination, are used by the pilot to perceive ground clearance. We conclude with an analysis of low-altitude military flight in which the perceptual and attentional demands of the components of flight are combined, and tasks are prioritized by their inherent demands as well as by mission and ground-avoidance requirements.

This chapter departs slightly from the others in this volume in that it is largely based on our experiences observing and participating in the training of U.S. fighter pilots to perform low-level flight tasks at the 162nd Fighter Weapons School of the Arizona National Guard at Tucson. The instructor pilots knew more about perception, attention, and performance in a practical sense than all the textbooks teach. In the time that we worked with these instructors, we discovered the problems of applying our land-bound theories and models to the remarkable airborne performance that we observed every day. We are particularly indebted to a young instructor, Capt. Milt Miller, who translated skills and understanding of the inherent problems of flying low and fast into a superb training program (Miller, 1983). In later chapters in this volume, models of pilot control are introduced by Wickens in chapter 7; a more formal analytic treatment is presented by Hess in chapter 8.

AERODYNAMICS OF MOTION: THE EFFECTS OF CONTROL INPUTS ON FLIGHT

Survival at low altitude requires that the pilot understand and continually consider the physical dynamics of the movement of his aircraft and the changes in those dynamics as a result of the control inputs that he makes. Specifically, the pilot needs to know how long it takes his aircraft to respond to his inputs.

Suppose a pilot is deliberately flying low, well below an upcoming ridge. How long can he delay changing his flight path until it is past that instant in time beyond which collision with the ridge becomes irreversible and inevitable? The answer, counting backward from the moment of impact, includes the time required for the pilot to perceive, decide, and respond to the upcoming ridge, as well as the time required for the plane to respond to the inputs from the controls. This instant in time, beyond which collision is unavoidable, is called *time-to-die.* Every maneuver performed near the ground has an associated time-to-die limit. Conversely, *free time* refers, in seconds, to all the time available to the pilot before he passes the time-to-die instant, when collision is irreversible. Free time describes how many seconds the pilot can use to attend to tasks other than ground clearance. Time-to-die and free time are critical concepts in our presentation of low-altitude flying.

In this section, we discuss how the physical dynamics of an aircraft are defined and specified; and then, through the consideration of some sample maneuvers, describe the relation between the aerodynamics of flight and time-to-die and free time when flying near the ground.

Descriptions of the Position and Movements of Aircraft in Relation to Control Inputs

Three parameters—G-force, altitude above the ground, and velocity vector—define the location of the aircraft in relation to the ground and its ongoing flight path through space.

G-force refers to movement of the aircraft with respect to gravity, that is, parallel to the lift axis, which is usually perpendicular to the axis of the wings. With wings level, initiating a climb exerts a downward force on the aircraft and its occupants proportional to the acceleration. The accelerating force of the climb is specified in Gs, or the multiple of the weight of the plane needed to produce the acceleration. A 3 G accelerating climb triples the weight of the plane (and the pilot within it as well) during the course of the acceleration. In a level turn, the lift axis remains perpendicular to the wings, as seen in Fig. 2.1. But the turning force generates centrifugal force, which requires more lift to maintain level flight; the steeper the bank angle, the more lift is needed. The forces resulting from lift in a turn, as in a climb, are specified in Gs.

Altitude above the ground (altitude AGL) specifies the perpendicular separation between the plane and the ground (or water) directly under it. Altitude AGL, the distance to the ground under the plane, is the most important referent for altitude in the low-altitude environment—reference to elevation above sea level is rarely used.

The *velocity vector* of the aircraft refers to the direction of travel through the air, not to the location of the aircraft with respect to the ground. The velocity vector is specified in three dimensions: the speed through the air, the angle between the path of flight and the horizontal (specifying the plane's elevation above or below the true horizontal), and the angle made between the path of flight and a

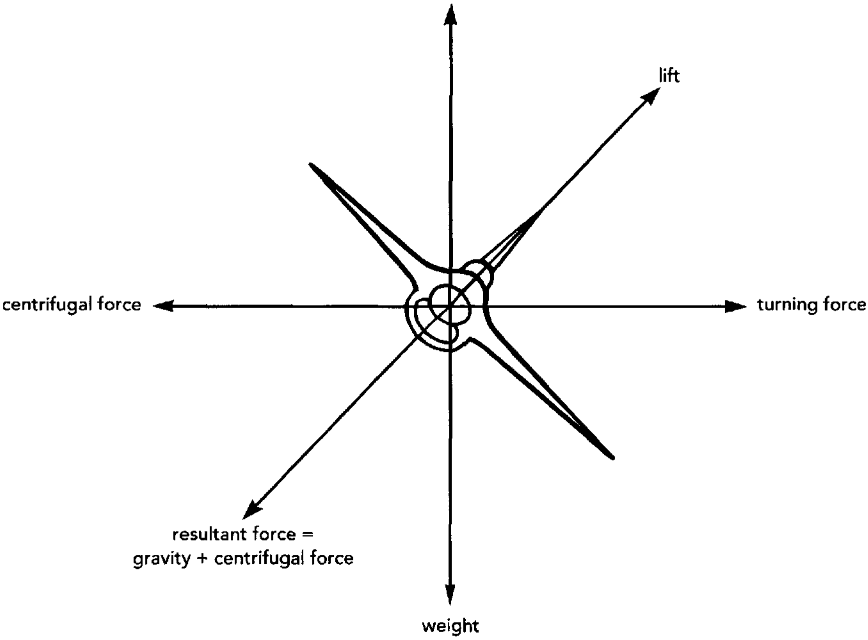


FIG. 2.1. A diagrammatic representation of the forces acting on an aircraft in a banked turn.

reference compass direction (azimuth), such as north. The second and third dimensions taken together define the flight path.

When the pilot applies some input to the aircraft's controls, the changes in G, altitude, and velocity vector define the aircraft's future position. Pushing the stick forward or backward controls the pitch axis of the aircraft; pulling the stick back lifts the nose, causing an ascent. Pushing the stick to the side controls the wing axis of the aircraft; moving the stick to the left lowers the left wing, initiating a descending turn to the left. To make a level turn to the left, the stick has to be moved to the left and simultaneously pulled back. The pull back adds lift to counteract the descent that would otherwise occur.

Aircraft also have a throttle, which changes the thrust exerted by the aircraft's power plant. Although adjustments of the throttle affect the aircraft's *velocity* through the air, military jet fighters are usually operated at a relatively constant (and high) throttle setting. Therefore, changes in aerodynamics of flight do not stem from engine power changes settings as much as from changes in stick position (e.g., pulling back on the stick, which initiates a climb, will, without additional thrust, also result in a decrease in velocity).

Except by momentary coincidence, the flight path of the plane is rarely the direction in which the nose is pointing. This means that the flight path is not aligned with the pitch (longitudinal) axis of the plane in level flight. The nose is usually higher than the flight path, with the amount of its elevation (called angle of attack) varying with the weight of the plane (which changes as fuel is consumed and weapons are expended), its G-loading, and its velocity. Therefore, to maintain level flight, the weight of the aircraft must be compensated for by a pull-back on the stick, which creates a nose-up attitude along its pitch axis (assuming upright flight).

All heavier-than-air aircraft have some degree of instability, with jet fighters being excessively unstable. Therefore, even when the pilot does not initiate new control inputs, the velocity vector and the altitude of a jet fighter continuously change unpredictably. This means that many of the control inputs that the pilot makes are needed just to maintain constant flight parameters. This instability forces frequent and often continuous attention to collision-avoidance tasks.

Some Sample Maneuvers and Their Associated Time-to-Die and Free Time

In the low-altitude environment, where ground-clearance tasks dictate most of the pilot's control inputs, small changes in velocity vector, altitude AGL, and G-forces create large changes in the time-to-die interval and therefore in the pilot's free time. We illustrate this by examining three examples of flight paths and maneuvers regularly performed at low altitude: straight and level flight, level turns, and ridge crossings as part of terrain masking. In each case, the concern is whether the aircraft is on a ground-collision course, and if so, how much time the pilot has while converging with the ground during which he can still initiate a recovery.

Straight and Level. Suppose while flying at 1,000 feet per second at 100 feet altitude AGL on a straight and level course over level terrain, the pilot stops attending to his velocity vector (because he is looking for his wingman, looking for a possible enemy aircraft, or changing a radio frequency, which requires a heads-down position in the cockpit). During this time his jet begins an unintended and minimal 1-degree descent toward the ground. This change in velocity vector starts slowly enough that unless the pilot pays attention to ground clearance or the flight path marker in his head-up display, the descent can continue without detection. This rate of descent is too small to be picked up quickly enough by most of his other flight instruments (e.g., attitude indicator, barometric altitude gauge, radar altimeter, vertical velocity indicator) or his vestibular system (see chap. 3).

Figure 2.2 shows the loss of altitude AGL as a function of time after the descent begins. This graph is pure physics and concerns the time it will take the aircraft to impact the ground. At this speed, a negative flight path angle of 1 degree with the horizontal produces a negative vertical velocity of 16 feet per second, so at 100 feet altitude AGL, impact with the ground occurs in just under 7

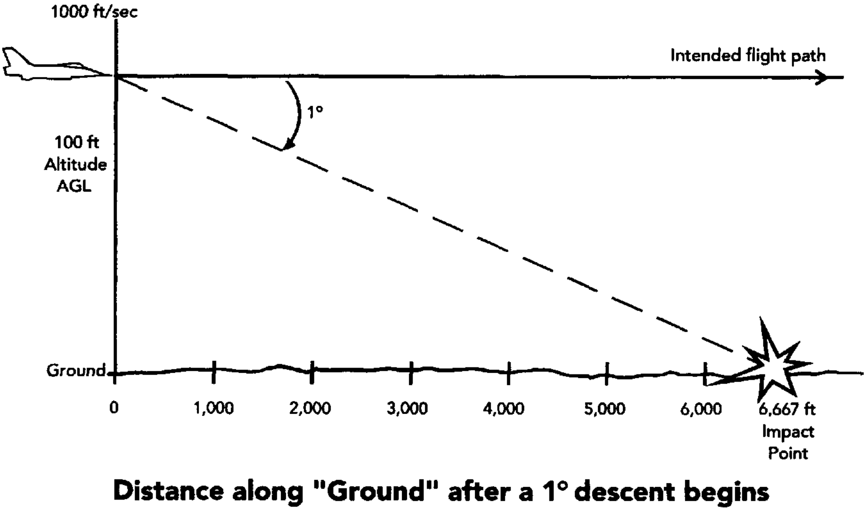


FIG. 2.2. An aircraft, traveling at 1,000 feet per second at 100 feet altitude AGL that begins a 1-degree unintended wings level descent will lose altitude at a constant 16 feet per second and will impact the ground in 6.67 seconds, at a location 6,667 feet from where the descent began.

seconds. Doubling the altitude AGL doubles the time until impact. Unfortunately, this is about the only maneuver in which the time until impact is linearly related to altitude AGL.

The free time for a 1-degree wings level descent from 100 feet altitude AGL is much shorter than the 6.7 seconds shown in Fig. 2.2. At what point in time does collision with the ground become irreversible, regardless of what the pilot does? Detecting the descent by the pilot takes some time, and after detection, a decision to act is needed. Then the pilot has to respond by pulling back on the stick, and then the aircraft itself needs to recover. Although the stick movement will produce a nearly instantaneous change in the orientation of the nose (angle of attack), the velocity vector changes from negative to positive more slowly; the plane continues mushing toward the ground, until the changed angle of the control surfaces of the aircraft begins to return the aircraft to a positive flight path angle. Miller's (1983) training manual shows that the detection, decision, and response times of the pilot and the response time of the aircraft consume 2.5 seconds, so the time-to-die is 2.5 seconds. Once the plane gets within 2.5 seconds of impact at this rate of descent, the pilot is dead meat, though he will live several seconds more. His free time at 100 feet altitude AGL in this example is just over 4 seconds—the time until he can no longer prevent impact.

The same physics and free time apply if, instead of a 1-degree change in the flight path angle of the velocity vector, the terrain changes from a level grade to a 1-degree upslope. Impact occurs in less than 7 seconds in the absence of a control input, and the pilot still has only 4 seconds in which to detect the change in terrain.

Level Turns. A very common maneuver at low altitude is to make a level turn—a horizontal change in direction while maintaining a constant altitude AGL. The pilot enters the turn by banking the aircraft into the turn while simultaneously pulling back on the stick, thereby adding G-forces parallel to the lift vector of the aircraft. The higher the bank angle (with the corresponding number of added G-forces), the faster the rate of turn, and the smaller the turning radius. Thus, the pilot controls the rate of turn and the turn radius through manipulation of the stick (with rarely any adjustment of the throttle).

If the pilot only banked, by moving the stick to the side, there would be no compensatory addition of G-forces to offset the loss of lift opposing gravity, and the aircraft would slip sideways and downward toward the ground. Consequently, to maintain a level turn with no loss or gain in altitude AGL, the pilot must exactly synchronize the degree of bank angle with the proper amount of G-forces added by also pulling back on the stick as he banks. For example, to go from wings level flight (1 G) to 30 degrees bank angle requires the addition of 0.15 G. An additional 30 degrees of bank needs another 0.85 G. Especially beyond 60 degrees of bank, Gs must be added in an ever-accelerating fashion, so that massive G-forces are needed to make very tight turns. (Because adding G-forces to the aircraft also adds them to the pilot, their physiological and psychological effects must also be considered. These are substantial and potentially overwhelming.)

The pilot can coordinate his bank angle and G-forces to maintain a level turn by watching the ground and the horizon out the canopy and adding or subtracting bank angle (or G) as needed to keep the turn level. To do this, he does not have to know the numbers, but he must monitor the ground or watch his flight path marker.

However, if he attends to some other flight maneuver or task, physics says the plane will descend if he has too much bank angle for the appropriate G or too little G for the appropriate bank angle. That descent is not linear with the amount of mismatch; altitude AGL is lost at an ever-increasing rate as the bank angle and G mismatch increases. For example, if a pilot enters an intended level 5-G turn while flying at 100 feet altitude AGL (which will remain level indefinitely if the bank angle [75 degrees] and G [5] match), but overbanks by 5 degrees, he will impact the ground in 3.7 seconds; with 10 degrees overbank, he will impact the ground in 2.6 seconds; and with 15 degrees overbank, impact occurs in only 1.9 seconds. These are time-to-die values; free time is much less. Miller uses 2.5 seconds for the time-to-die value for an intended level turn—the time to perceive the mismatch, decide what to do, react, and have the plane react. Therefore, for a 5-G intended level turn at 100 feet altitude AGL with a 5-degree overbank, if impact occurs in 3.7 seconds and time-to-die is 2.5, the free time is barely more than a second. It is zero for a 10-degree overbank (impact is in 2.6 seconds and time-to-die is 2.5 seconds), and no recovery is possible from a 15-degree overbank at 100 feet altitude AGL. Given these numbers and that overbanking is difficult to detect when performing other tasks, Miller teaches that there is no free time during a level turn at 100 feet altitude AGL or less and barely a second at 200 feet altitude AGL.

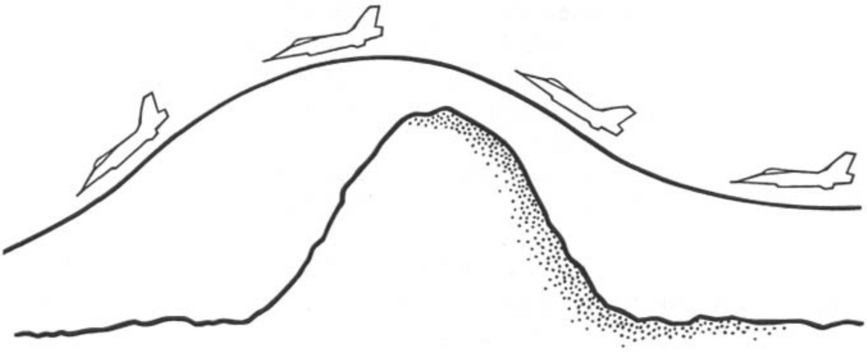
Overbanking can occasionally be intentional, as when a pilot wishes to make a rapid descending turn. What a pilot must know about this method of losing altitude, compared to merely entering a wings-level unaccelerating descent, is that the altitude AGL loss in a descending turn is an accelerating function of time, not the linear one shown in Fig. 2.2. The aircraft approaches the ground at an ever-increasing rate. Free time disappears at an ever increasing rate.

Ridge Crossing During Terrain Masking. The third example is a frequently performed maneuver used during terrain masking, in which the pilot maneuvers his aircraft to follow the contours of the ground, using combinations of straights, turns, and dives, as well as rolls, inverted flight, and other high-intensity maneuvers. The goal is to keep altitude AGL below 200 feet or less, regardless of the changes in the terrain, to minimize visual and electronic exposure.

To cross a ridge, however, the pilot has to expose himself by flying higher than the surrounding terrain. To minimize his risk, the pilot must keep his altitude AGL at the ridge line as low as possible without actually hitting the ridge. For aerodynamic reasons, this increases the chances of hitting the ground on the other side. The complexity of ridge crossing is illustrated in Fig. 2.3, which shows two different ways to perform the maneuver.

Figure 2.3 (top panel) shows in profile the flight path of a fighter approaching and crossing a ridge line head-on. The approach is with wings level, followed by a rapid wings level ascent up the ridge wall until the ridge top is just cleared (a few feet is sufficient!). At the ridgeline, the pilot pushes the stick forward to make a wings level descent down the other side. This direct approach creates three problems for the pilot: the plane balloons over the ridge, with too much exposure on the far side (it takes more time to push a plane down than to pull it up); the nose of the plane blocks his view of the other side of the ridge as he comes over, so he cannot see if there is a second ridge waiting to eat him; and the pull down on the far side exerts negative G-forces on his body, pulling his body out of his seat and his last meal into his throat (or higher). For each of these reasons, this method of ridge crossing is never preferred.

The lower panel of Fig. 2.3 shows one typical solution, one that takes advantage of the great maneuverability of jet aircraft. As he begins his approach to the ridge, the pilot both begins to pull up and to roll his aircraft about its velocity vector, so that he crosses the highest part of the ridge nearly upside down. To get back down to the valley bottom on the other side, he either rolls back or the rest of the way around (depending on the angle at which he approached the ridge), all the while continuing to pull back on the stick. Now gravitational forces continue to be positive throughout the entire maneuver, keeping his last meal where it belongs; being inverted, he can look out the top of the canopy so that the nose of his aircraft is not in his way. He can see the entire area over the ridge as soon as



Straight-over Ridge Crossing

Roll-Turn Combination Ridge Crossing

FIG. 2.3. Two examples of crossing a ridge perpendicular to the direction of flight. (a) The pilot makes a wings level climb up the ridge and then, after passing over the ridgeline, makes a wings level descent. (b) The pilot rolls inverted and pulls going up the front side and over the top of the ridge, and then rolls the remainder of the way around, pulling down the backside until he resumes level flight.

he clears the top of the ridge; most importantly, his greater maneuverability under positive Gs gets him back down faster without the great exposure. Partway down the backside of the ridge, he rolls out wings level to continue into the new valley. As can be seen from the lower panel of Fig. 2.3, the pilot has his velocity vector pointing toward the ground for nearly the entire time spent in this ridge crossing maneuver—a series of intentional dives toward the ground.

We have briefly sketched three maneuvers and for each shown the relation between time and altitude loss as determined by physical principles of aerodynamics. Each of these relationships defines a time-to-die for any given altitude AGL, as a function of planned or unintentional deviations from level flight. These three maneuvers have very different time-to-die values and are very different in their sensitivities to altitude AGL. For example, consider the two maneuvers designed to maintain level flight. Straight and level is a low-intensity maneuver, in the sense that the pilot has lots of free time to perform tasks other than monitoring his ground clearance and can easily buy more free time by adding altitude AGL. In contrast, a level turn is a high-intensity maneuver, without much free time and little gain in free time when performed at a higher altitude AGL. Any maneuver in which the plane actually converges with the ground at low altitude, such as an intentional dive, is of even greater intensity and allows the pilot no free time at all, as the remaining altitude approaches the minimum needed to recover from the dive.

These examples of maneuvers show how free time changes as a function of maneuver intensity and altitude AGL. When pilots know and understand the aerodynamics of the maneuvers of their aircraft, then they can always know how much free time they have for tasks other than ground clearance, and they should never fly into the dirt.

Although we discussed three maneuvers for illustrative purposes, they are not a random sample. The low-altitude environment over hostile territory involves primarily high-intensity maneuvers. One measure of intensity is the amount, variability, and onset rate of G-forces exerted on the pilot (and plane)—the higher the G-forces, the greater the variability; and the more rapid the onset time, the higher the intensity of the maneuver. As an example, Fig. 2.4 shows a 1-minute sample

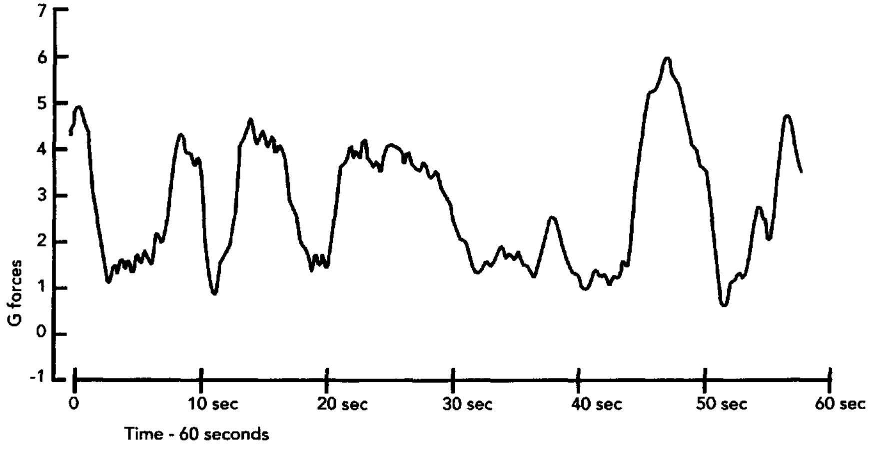


FIG. 2.4. A 1-minute record of changing G-forces exerted on an A-10 pilot during combat maneuvering at low altitude.

of the G-forces exerted on an A-10 pilot by his maneuvers over a 30-minute period of low-altitude attack and masking (Gillingham, Makulous, & Tays, 1982). The entire record is taken from less than 500 feet altitude AGL, with most of it from less than 150 feet altitude AGL. Notice that this A-10 pilot did not pull negative Gs but is always between +1 and +6 Gs, very rarely maintaining a peaceful 1 G for even a second. In any 10-second period, he dives, pulls, turns, and jinks each several times. The onsets are very rapid. This is typical of high-intensity maneuvering when flying a mission near the ground. This figure defines many of the problems for pilots flying in this environment.

SOURCES OF INFORMATION THAT SPECIFY GROUND CLEARANCE

If a pilot knew his altitude AGL and velocity vector, he could look at upcoming terrain and never impact it. In this section, we describe the sources of information available to the pilot that specify his altitude AGL, velocity vector, ground track, and distance to objects as he flies over natural terrain. As we show, sources of information are neither equally available nor equivalent in terms of accuracy, timing, or ease of being processed. To appreciate these differences, we focus here on the information content itself; in the following section, we describe how that information is processed and used.

The four sources of the relevant information that a pilot can use in order to perceive his ground clearance include (a) visual information from the surface of the terrain; (b) vestibular information from the changes in gravitational forces acting on the pilot's body (see chap. 3); (c) symbolic information (primarily visual) from flight instruments and displays inside the cockpit (see chap. 5); and (d) information acquired by the pilot before the flight. The first three stress concurrent sources, so that their content changes constantly as the pilot moves; the fourth is more cognitive and is available to select and modify the first three.

For each of these four sources, we first describe the source itself and the geometry and physics (and neurophysiology where necessary) that account for a correlation between changes in the aircraft's location and changes in the content of the information from the source. We then describe the dependability of the source.

A dependable source of information is one that is always available for the pilot to use and whose change in content is highly correlated with changes in the relative position of the aircraft vis-à-vis the ground. A source that is only sometimes present is less dependable. A source that produces a change indicating divergence from the ground when, in fact, the aircraft is converging with the ground is a widowmaker.

Visual Information From the Surface of the Terrain

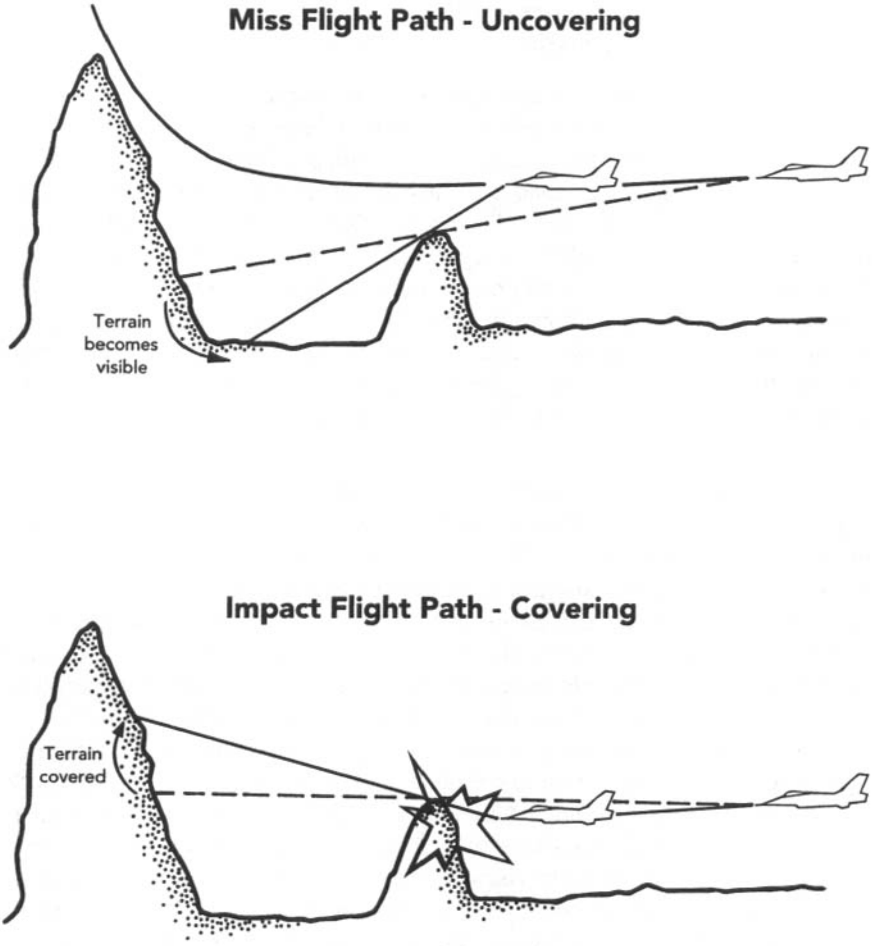
The most important source of information for low-altitude flying comes from the way the terrain reflects unique patterns of light to the pilot's eyes. Pilots routinely fly over all naturally existing terrains, some with properties that reflect patterns of light that are highly informative of their distance, orientation, and regularity with respect to the pilot and some that provide little information about their position relative to him. Therefore, analysis of this source of information requires description of the relevant terrain properties. Four independent properties of terrains are critical for their informativeness about ground clearance: the degree of irregularity of projections above their surface, the amount of surface texture they possess, linear perspective arising from the angle of viewing the terrain, and the amount of fine detail present on objects on the terrain.

Terrain Contour Irregularity. Terrain contour varies from rugged to flat. Typical examples of rugged terrains include hills, mountains, and extents containing many vertically projecting objects, such as trees, buildings, or towers. Almost invariably, rugged terrain also has substantial surface texture (as explained later). At the other extreme, flat terrains are characterized by an absence of surface irregularities in height. Typical examples of flat terrain contours include an extended body of water, a large prairie or desert without trees or other vertical projections, and a dry lake bed. Flat terrains may or may not have much surface texture.

Moving over rugged terrain produces changes in the dynamic patterning of light reflected from the terrain to the pilot's eyes that are highly correlated with changes in the pilot's altitude AGL, velocity vector, and distance to particular objects on the ground. Therefore, rugged terrain is highly informative about ground clearance. The primary visual source of this information is the dynamic optical occlusion of far surfaces by the interposition of near ones in the pilot's line of sight as he flies over the irregularities (see Owen, 1981, for examples and Cutting, 1986, for a review).

For dynamic optical occlusion to occur, there must be differences in the elevation of parts of the terrain. A flat surface has nothing in the near ground that projects upward enough to occlude farther objects or terrain. Therefore, flat terrains are relatively uninformative to a pilot concerning his ground clearance.

To illustrate the geometric basis for the informativeness of dynamic occlusion (i.e., the high correlation between changes in occlusion and changes in ground clearance), Fig. 2.5 shows a side-profile view of a terrain in which a near ridge is interposed between the pilot and the higher far ridge. The dynamic (changing) optical occlusion of the far ridge precisely specifies the velocity vector of the aircraft and therefore whether the plane will clear the near ridge. As the pilot approaches the near ridge, if more and more of the far ridge becomes visible (as



Miss Flight Path - Uncovering

Impact Flight Path - Covering

FIG. 2.5. A pilot can determine whether his velocity vector will carry him over a nearby hill by noting the nature of the changing visibility of any farther hill. (a) The flight path is above the near hill, and more and more of the far hill becomes *visible* as the pilot approaches. (b) In a flight path that will impact the low hill, the pilot should have noticed that more and more of the far hill was being occluded from view as it was approached.

in the top of Fig. 2.5), his velocity vector must be above the crest of the near ridge to clear it. In contrast, if more of the far ridge disappears from view as the pilot approaches it (as in the bottom of Fig. 2.5), his velocity vector must be below the crest of the near ridge, and the plane will impact it. A near surface covering up a far one as it is approached signals impending collision. This is probably the single most important source of information that allows a pilot to fly safely up an irregularly rising valley without colliding with the outcrops.