**Improving Aviation Safety with Information Visualization:
Airflow Hazard Display for Helicopter Pilots**

by

Cecilia Rodriguez Aragon

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Committee in charge:

Professor Marti Hearst, Co-Chair
Professor Shankar Sastry, Co-Chair
Professor Ruzena Bajcsy
Professor Paul Wright

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Abstract

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Many aircraft accidents each year are caused by encounters with airflow hazards near the ground, such as vortices or other turbulence. While such hazards frequently pose problems to fixed-wing aircraft, they are especially dangerous to helicopters, whose pilots often have to operate into confined areas or under operationally stressful conditions. Pilots are often unaware of these invisible hazards while simultaneously attending to other aspects of aircraft operation close to the ground.

Recent advances in aviation sensor technology offer the potential for aircraft-based sensors that can gather large amounts of airflow velocity data in real time. This development is likely to lead to the production of onboard detection systems that can convey detailed, specific information about imminent airflow hazards to pilots. A user interface is required that can present extensive amounts of data to the pilot in a useful manner in real time, yet not distract from the pilot's primary task of flying the aircraft.

In this dissertation, we address the question of how best to present safety-critical visual information to a cognitively overloaded user in real time.

We designed an airflow hazard visualization system according to user-centered design principles, implemented the system in a high fidelity, aerodynamically realistic rotorcraft flight simulator, and evaluated it via usability studies with experienced military and civilian helicopter pilots.

We gathered both subjective data from the pilots' evaluations of the visualizations, and objective data from the pilots' performance during the landing simulations. Our study demonstrated that information visualization of airflow hazards, when presented to helicopter pilots in the simulator, dramatically improved their ability to land safely under turbulent conditions.

Although we focused on one particular aviation application, the results may be relevant to user interfaces and information visualization in other safety-related applications where the user's primary task is something other than looking at the computer interface, such as emergency response, air traffic control, or operating a motor vehicle.

Professor Marti Hearst
Dissertation Committee Co-Chair

Professor Shankar Sastry
Dissertation Committee Co-Chair

In loving memory of my mother, Katinka Rodriguez

Table of Contents

Dedication i
Table of Contents ii
List of Figures vii
List of Tables xiii
Glossary xvi
Acknowledgments xix

Chapter 1 ■ Introduction 1
1.1 Overview 1
1.2 Background 2
1.3 Focus on Helicopter Pilots 12
1.4 New Sensor Technology 16
1.5 Dissertation Outline 17

Chapter 2 ■ Related Work 19
2.1 Human Factors in Aviation 20
2.1.1 Cockpit Automation 21
2.1.2 FAA Regulations Governing Cockpit Automation 22
2.1.3 Human-Centered Aircraft Automation 22
2.1.4 Studies of Attention in the Cockpit 23

2.1.5 Studies of Head-Up Displays (HUDs) 24
2.2 Aviation Displays 27
2.2.1 Synthetic Vision Systems 27
2.2.1.1 Augmented Reality Displays 28
2.2.2 Weather Prediction and Visualization 29
2.2.2.1 NASA AWIN 29
2.2.2.2 NASA TPAWS 30
2.2.2.3 Microburst Detection 30
2.2.2.4 Other Weather Visualization Systems 31
2.2.3 Flight-Deck Display of Neighboring Aircraft Wake Vortices 31
2.3 Information Visualization 33
2.4 Flow Visualization 33
2.4.1 Computational Flow Visualization Techniques 34
2.4.1.1 Direct Flow Visualization 35
2.4.1.2 Texture-Based Visualization 38
2.4.1.3 Geometric Flow Visualization 40
2.4.1.4 Feature-Based Visualization 43
2.4.2 Experimental Flow Visualization 44
2.4.2.1 Particle Traces 46
2.4.2.2 Dye Injection 46
2.4.2.3 Schlieren Techniques 46
2.4.3 Usability Studies of Flow Visualization 46
2.4.4 Flow Visualization for Pilots 47
2.4.4.1 Human-Centered Design 47
2.5 Helicopter Shipboard Operations 48
2.5.1 Navy "Dynamic Interface" 50
2.5.2 Operational Envelopes 51
2.5.3 Pilot Ratings of Landing Difficulty 55
2.5.3.1 Cooper-Harper Rating Scale 55
2.5.3.2 US Navy DI Pilot Rating System (PRS) 56
2.6 Summary 58

Chapter 3 ■ Low Fidelity Prototype 59
3.1 Introduction 59
3.2 Hazard detection architecture 60
3.2.1 Sensors/detection 60
3.2.2 Classification/analysis 62
3.2.3 Display to the pilot (user interface) 63
3.3 Motivation for visual interface usability study 64
3.4 Selection of Platform for Low-Fidelity Prototype 66
3.5 Methodology 68
3.6 Participants 73
3.7 Results 74
3.7.1 Color 75
3.7.2 Transparency 78
3.7.3 Depth Cues 78
3.7.4 Texture 79
3.7.5 Shape 79
3.7.6 Motion (Animation) 85
3.7.7 Audio 87
3.7.8 General Considerations 87
3.8 Conclusions 88
3.8.1 "The Holy Grail" 89

Chapter 4 ■ Flight Simulation Study 90
4.1 Introduction 90
4.2 Implementation of Flight Simulation Interface 91
4.2.1 Design and Implementation Process 92
4.3 Flight Simulation Study 106
4.3.1 Study Overview and Issues 106
4.3.2 Study Protocol and Design 108
4.3.3 Approach Description 109
4.3.4 Approach Scenarios 110
4.3.5 Landing Difficulty Level 111

4.3.5.1 Landing difficulty 1 (LD 1) – Control 112
4.3.5.2 Landing difficulty 2 (LD 2) 112
4.3.5.3 Landing difficulty 3 (LD 3) 112
4.3.5.4 Landing difficulty 4 (LD 4) 113
4.3.6 Order of Presentation 113
4.3.7 Dependent Variables 114
4.3.8 Hypotheses 115
4.3.9 Participants 115
4.3.10 Equipment 117
4.3.10.1 Simulator Validation and Quality 117
4.3.10.2 Simulator Specifications 118
4.4 Results 119
4.4.1 Choice of Tests for Statistical Analysis 120
4.4.2 Primary Results 121
4.4.2.1 Summary of Crash Statistics 121
4.4.2.2 Hypothesis 1 confirmed 122
4.4.2.3 Hypothesis 2 confirmed 124
4.4.2.4 Hypothesis 3 126
4.4.2.5 Hypothesis 4 confirmed 128
4.4.2.6 Control group (LD 1) 130
4.4.2.7 Learning effects 132
4.4.3 Ancillary Results 135
4.4.3.1 Go-Around Rate Analysis 135
4.4.3.2 Landing Rate Analysis 139
4.4.3.3 Analysis by Pilot Experience Level 141
4.4.3.4 Analysis of Subjective Data from Pilot Evaluations 146
4.5 Conclusions 173

Chapter 5 ■ Conclusions and Further Work 174
5.1 Summary of Results 174
5.2 Further Work 175
5.2.1 Further data analysis 176

5.2.2 Further studies 177
5.2.3 System development and deployment 178
5.2.4 Background or more basic research 178
5.2.5 Extensions to other areas 179
5.3 Conclusions 179

Appendices ■ 181
A.1 Materials for Low-Fidelity Prototype 181
A.1.1 Low-Fidelity Prototype Description 182
A.1.2 Low-Fidelity Prototype Usability Tests Script 184
A.2 Materials for Flight Simulation Usability Study 193
A.2.1 Scripts and Briefings 193
A.2.1.1 Overall Script for Airflow Hazard Simulator Study 193
A.2.2 Forms for Pilot to Fill Out 198
A.2.3 Order of Flight 200
A.2.4 Approach Forms 202
A.2.5 Post-Flight Debrief Script 204
A.2.6 Post-Simulation Pilot Evaluation 206
A.3 Pilot Comments on ART Simulator Quality 209

References ■ 212

List of Figures

Figure 1. The crash of Delta Flight 191 (US Govt. image, http://oea.larc.nasa.gov/trailblazer/SP-4216/toc.html) 3

Figure 2. Microburst diagram (US Govt. image, http://oea.larc.nasa.gov/trailblazer/SP-4216/toc.html) 3

Figure 3. Why microbursts are dangerous to landing aircraft (US Govt. image, http://www.ncar.ucar.edu/) 4

Figure 4. H-46 dual-rotor helicopter approaching ship (all 7 frames are US Govt. images, courtesy K. Long) 5

Figure 5. Helicopter approach becomes slightly low as it nears ship 6

Figure 6. Helicopter landing gear does not clear ship deck 6

Figure 7. Landing gear becomes entangled in net 7

Figure 8. Pilot attempts to pull up, but helicopter enters dynamic rollover 7

Figure 9. Helicopter cannot recover 8

Figure 10. Unfortunately, there were several fatalities in this accident 8

Figure 11. C-2A Greyhound is approaching for an aircraft carrier landing (all 6 frames are US Govt. images, courtesy K. Long) 9

Figure 12. Aircraft begins to drift slightly left of centerline 10

Figure 13. Aircraft deviates well left of centerline due to unrecognized crosswind 10

Figure 14. Aircraft lands on left edge of carrier runway 11

Figure 15. Aircraft landing gear slips off deck edge because pilot cannot compensate for crosswind 11

Figure 16. End result: an expensive and embarrassing accident 12

Figure 17. Turbulent flow and vortex formation on leeward side of obstacles (US Govt. image, http://www.nws.noaa.gov) 13

Figure 18. Turbulent airflow over vegetation (US Govt. image, http://www.nws.noaa.gov) 13

Figure 19. Helicopters landing on shipboard have to contend with high levels of pitch and roll (photo by K. Long, US Govt. image, courtesy of K. Long).............................. 15

Figure 20. Lidar schematic (US Govt. image, http://www.ghcc.msfc.nasa.gov/sparcle/sparcle_tutorial.html)............................... 17

Figure 21. An example of HUD symbology (US Govt. image, courtesy of W. Holforty, labels added by C. Aragon).. 25

Figure 22. Synthetic vision on a head-up display: pilot advisory of runway conflict (US Govt. image, http://www.larc.nasa.gov) 26

Figure 23. Typical weather radar imagery (color-coded by intensity of echoes) (US Govt image, http://nix.nasa.gov).. 29

Figure 24. Holforty's wake turbulence cockpit display (US Govt. image, courtesy of W. Holforty) 32

Figure 25. Example of direct flow visualization - wind arrows superimposed on satellite photo (US Govt. image, http://www.weather.noaa.gov) 36

Figure 26. Example of direct flow visualization: rotor wake vortices (US Govt. image, http://ails.arc.nasa.gov/Images/Aeronautics/AC76-0585.5.html)............................ 36

Figure 27. Example of direct flow visualization - 2D visualization of turbulence (color-coded by velocity) (US Govt. image, http://ails.arc.nasa.gov) 37

Figure 28. Example of direct flow visualization - 2D wind arrows computed by SRI's TerraVision (image courtesy of SRI International, http://www.ai.sri.com/TerraVision).. 37

Figure 29. Example of texture-based flow visualization - Space shuttle flow depicted using line-integral convolution (LIC) (US Govt. image, http://www.nas.nasa.gov/Groups/VisTech) 38

Figure 30. Example of texture-based visualization - spot noise flow visualization (US Govt. image, http://www.llnl.gov/graphics/gifs/spotKlein_600.gif) 39

Figure 31. Example of texture-based visualization - Monochrome texture splats with colored textures show wind direction in North America (US Govt. image, http://www.llnl.gov/graphics/splats.html) 39

Figure 32. Example of geometric flow visualization: instantaneous streamlines (US Govt. image, http://www.nas.nasa.gov/Groups/VisTech) 41

Figure 33. Example of geometric flow visualization - Velocity contours in 2D (US Govt. image, http://www.nas.nasa.gov/Groups/VisTech) 41

Figure 34. Example of geometric flow visualization - Timelines: unsteady flow visualization (US Govt. image, http://www.nas.nasa.gov/Groups/VisTech) 42

Figure 35. Example of geometric flow visualization - Flow volumes (US Govt. image, http://www.llnl.gov/graphics/flow.html) 42

Figure 36. Example of geometric flow visualization - SRI's TerraVision: visualizing clear air turbulence (image courtesy of SRI International, http://www.ai.sri.com/TerraVision).. 42

Figure 37. Example of feature-based flow visualization - Space shuttle shock waves (US Govt. image, http://www.nas.nasa.gov/Groups/VisTech) 43

Figure 38. Example of experimental flow visualization - Wake vortex visualized by smoke and color enhancement (US Govt. image, http://www.larc.nasa.gov) 45

Figure 39. Example of experimental flow visualization - Schlieren photograph of a shock wave created by a bullet (photo by A. Davidhazy, reprinted with permission, http://www.rit.edu/~andpph/text-schlieren.html) 45

Figure 40. First US Navy shipboard helicopter landing: Sikorsky XR-4 aboard SS Bunker Hill, May 1943 (US Govt. image, courtesy of K. Long) 49

Figure 41. Helicopter accidents and incidents occur each year (US Govt. image, courtesy K. Long) 50

Figure 42. Helicopter landing on shipboard (photo by K. Long, US Govt. image, courtesy of K. Long).. 51

Figure 43. Shipboard rotorcraft operational envelope (US Govt. image, courtesy of K. Long) 53

Figure 44. Navy shipboard rotorcraft testing yields extensive quantities of data and knowledge (US Govt. image, slide courtesy of Kurt Long) 54

Figure 45. The Cooper-Harper Handling Qualities Rating Scale (US Govt. image, courtesy of K. Long) 56

Figure 46. US Navy Dynamic Interface Pilot Rating Scale (PRS) (US Govt. image, slide courtesy of Kurt Long).. 58

Figure 47. Lidar schematic (reprinted with permission by T. Duck, http://aolab.phys.dal.ca/pages/LidarBasics).. 61

Figure 48. A helicopter-mounted lidar system undergoing test flights at the Japan Aerospace Exploration Agency (photo courtesy of Naoki Matayoshi).................... 62

Figure 49. Developing turbulent or swirling flow (reprinted with permission by D. Thompson, http://www.erc.msstate.edu/~dst/research_new/feature_mining/detection/swirling_gallery.shtml) 63

Figure 50. USS Spruance DD 963 (US Govt. image, courtesy of K. Long) 66

Figure 51. Rhino3D model of DD 963 67

Figure 52. As simulated in Rhino3D, this is the beginning of the helicopter's approach to DD963; 180 degrees off and abeam the landing spot 70

Figure 53. The helicopter continues the approach toward the ship. A sample hazard indicator is visible over the landing spot. 70

Figure 54. Helicopter turns onto final approach. To the right of the image is a menu of layers in Rhino3D; various hazard indicators can be turned on and off with a click. 71

Figure 55. Helicopter established on final approach 71

Figure 56. Helicopter is on short final, approaching landing spot on ship deck aft of hangar superstructure. DD963 only has one landing spot. 72

Figure 57. Helicopter is about to land aft of ship hangar. Hazard indicator can be clearly seen. Pilot can make comments on shape, color, transparency, etc. and have indicator modified as he speaks. 72

Figure 58. Color choice for hazard indicator: green 76

Figure 59. Color choice for hazard indicator: blue 76

Figure 60. Color choice for hazard indicator: yellow 77

Figure 61. Hazard indicator shape: rectilinear 80

Figure 62. Hazard indicator shape: open spiral 80

Figure 63. Hazard indicator shape: open rectangles 81

Figure 64. Hazard indicator shape: spiral 81

Figure 65. Hazard indicator shape: cloud 82

Figure 66. An example of unsuccessful imagery in the low-fidelity prototype -- a series of yellow rings to represent hazardous airflow 83

Figure 67. The ring symbology appears similar to the "highway-in-the-sky" tunnel symbology used on HUDs, and therefore may confuse the pilot or entice them to enter the "tunnel" 84

Figure 68. Example of tunnel-in-the-sky or highway-in-the-sky symbology (US Govt. image, courtesy of W. Holforty) 85

Figure 69. Animated gif showing airflow over ship (US Govt. image, courtesy of K. Long) 86

Figure 70. ART flight simulator with pilot in front of projection screen and operator at rear console 92

Figure 71. Sikorsky UH-60 Seahawk helicopter (US Govt. image, http://www.arc.nasa.gov) 93

Figure 72. LHA steaming, loaded with aircraft (US Govt. image, courtesy of K. Long) 93

Figure 73. Photo from ART flight simulator, labeled: landing spots and hazard locations for the four scenarios on the LHA-1 ship 94

Figure 74. ART simulator interface: checkpoint for starboard approach with high winds and hazard indicator visible 97

Figure 75. Visual hazard indicators used in the study for the four scenarios, Aft, Bow, Port, and Starboard (actual indicators were more translucent than depicted)........ 98

Figure 76. Hazard indicator (yellow, caution) - Aft scenario 100

Figure 77. Hazard indicator (yellow, caution) - Bow scenario 101

Figure 78. Hazard indicator (yellow, caution) - Port scenario 102

Figure 79. Hazard indicator (yellow, caution) - Starboard scenario 103

Figure 80. ART simulator interface for entering checkpoints for a set of approaches... 105

Figure 81. ART simulator instrument panel 119

List of Tables

Table 1. Simplified representation of airflow hazard detection system............................ 60

Table 2. Simulator scenario descriptions 96

Table 3. Table of 32 approaches with simulator variables for each approach. 28 approaches were used in the study; 4 approaches (A0, B0, P0, S0) with light winds were designated practice approaches and data was not recorded for them............. 104

Table 4. Landing difficulty levels 111

Table 5. Simulated Approach Orders.. 114

Table 6. Pilot Demographics.. 116

Table 7. Crash Statistics for All Landing Difficulties 122

Table 8. Landing Difficulty 3 - Crash Data 123

Table 9. Landing Difficulty 4 - Crash Data 125

Table 10. Landing Difficulty 2 - Crash Data 127

Table 11. Probe 6 Results 128

Table 12. Probe 21 Results 129

Table 13. No significant difference between crash rates at LD 1 (control) and LD 2 with hazard indicator and LD 3 with hazard indicator... 131

Table 14. No apparent learning effects in study 132

Table 15. Probe 17 Results 133

Table 16. No evidence for learning effects or other global effects as a function of order flown 134

Table 17. Go-Around Statistics for All Landing Difficulties 136

Table 18. Landing Difficulty 2 - Go-Around Data 137

Table 19. Landing Difficulty 3 - Go-Around Data 138

Table 20. Landing Statistics for All Landing Difficulties 139

Table 21. Landing Difficulty 2 - Landing Data 140

Table 22. Pilots grouped by experience level 141

Table 23. Crash statistics for less experienced pilots (group of 4) 142

Table 24. Crash statistics for moderately experienced pilots (group of 7) 143

Table 25. Crash statistics for highly experienced pilots (group of 4) 144

Table 26. No significant difference between pilot groups based on experience level.... 146

Table 27. Probe 1 Results 147

Table 28. Probe 2 Results 148

Table 29. Probe 3 Results 149

Table 30. Probe 4 Results 150

Table 31. Probe 5 Results 151

Table 32. Probe 7 Results 153

Table 33. Probe 8 Results 154

Table 34. Probe 9 Results 156

Table 35. Probe 10 Results 157

Table 36. Probe 11 Results 158

Table 37. Probe 12 Results 159

Table 38. Probe 13 Results 160

Table 39. Probe 14 Results 161

Table 40. Probe 15 Results 163

Table 41. Probe 16 Results 164

Table 42. Probe 18 Results 166

Table 43. Probe 19 Results 167

Table 44. Probe 20 Results 168

Glossary

Accident	an occurrence associated with the operation of an aircraft which takes place between the time any person boards the aircraft with the intention of flight and the time all such persons have disembarked, and in which any person suffers death or serious injury or in which the aircraft receives substantial damage
AGL	Above Ground Level
AIM	Aeronautical Information Manual
Air Boss	On Navy ships, the person who directs all aspects of flight deck operations from the carrier's control tower, including launching, recovery and shipboard handling of all aircraft
Anemometer	An instrument that measures wind speed and direction
ATC	Air Traffic Control
CAT	Clear Air Turbulence
CDTI	Cockpit Display of Traffic Information
DOT	Department of Transportation

FAA Federal Aviation Administration

FAR Federal Aviation Regulations

FMS Flight Management System

GA General Aviation

Go/No-Go Decision Pilot's decision whether or not to operate aircraft

Go-Around Aborted landing (see Waveoff)

GWIS Graphical Weather Information System

HDD Head-Down Display

HUD Head-Up Display -- A transparent screen mounted in front of the pilot's windshield on which pertinent data from flight instruments are projected, eliminating the need to look down into the cockpit to read instruments

IFR Instrument Flight Rules – regulations under which flight is conducted solely by reference to instruments and not by reference to the view out the cockpit

IMC Instrument Meteorological Conditions – conditions under which flight must be conducted under IFR

Incident An occurrence other than an accident, associated with the operation of an aircraft, which affects or could affect the safety of operations

Knot Unit of airspeed equivalent to 1.2 miles per hour

Low Level Wind Shear A sudden change in wind direction and speed occurring near the surface

Microburst Small, very intense downdraft that descends to the ground, often associated with thunderstorms

MSL Mean Sea Level

NAS National Airspace System

NASA National Aeronautics and Space Administration

NATOPS	The Naval Air Training and Operating Procedures Standardization program, responsible for rules and regulations governing the safe and correct operation of all naval aircraft
NM	Nautical mile (6000 feet)
NTSB	National Transportation Safety Board
PFD	Primary Flight Display
PIV	Particle Image Velocimetry
PRS	Pilot Rating Scale
Rotorcraft	heavier-than-air aircraft that depends principally for its support in flight on the lift generated by one or more rotors
SA	Situational Awareness
TAS	True Airspeed
TCAS	Traffic Alert and Collision Avoidance System
TRACON	Terminal Radar Approach Control
VFR	Visual Flight Rules
VMC	Visual Meteorological Conditions
Waveoff	Aborted landing (also see Go-Around)

Chapter 1 ■

Introduction

1.1 Overview

Much research on information visualization has focused on office environments, where it is assumed that the user's attention will be directed exclusively to the visualization interface. However, an area ripe for study is the use of information visualization in environments in which the user's primary task is something other than looking at the computer interface. This is particularly critical in safety-critical operational environments, such as emergency response, air traffic control, and operating any motor vehicle, where technology is increasingly making available additional useful information to already overloaded operators. For example, driving safety of automobiles might be improved by projecting sensor data, such as heat readings indicating pedestrians or animals ahead of the car on a foggy day, onto the driver's windshield. It is an open question how such sensor data should be presented to be simultaneously useful and safe.

In this dissertation we describe the design of a system of information visualization of airflow hazards for helicopter pilots. We describe our process of user-centered design, starting with a study of prior research that informed the design of a low-fidelity prototype of the system. We discuss the iterative procedures we used to design the system, how we implemented it in a high-fidelity rotorcraft flight simulator, and finally present the design, experiment setup, and results of a study in which information visualization of airflow hazards, when presented to helicopter pilots in a highly realistic simulator, dramatically improved their ability to land safely under turbulent conditions. For this problem, we find that the kind of visualization needed to improve operational safety is much simpler than that needed for analysis of such hazards. This is a result that has been observed previously within the field of information visualization [101].

In this chapter, we describe the flight safety problem, illustrating it with a series of frames from two videos depicting aircraft accidents where airflow hazards were implicated. We explain why we chose to focus on helicopter pilots, and specifically on helicopter-shipboard landings. Then we discuss a potential solution in the form of new sensor technology. We conclude the chapter by outlining the rest of the thesis.

1.2 Background

Turbulence and other wind-related conditions were implicated in nearly 10% of the over 21,000 aircraft accidents in the U.S. National Transportation Safety Board accident database from 1989-99 [35]. Airflow hazards occurring near the ground can be deadly even to airliners (Figure 1); there have been hundreds of fatalities in the United States in the last two decades attributable to airliner encounters with microbursts and low level wind shear alone [126]. (Microbursts are small, very intense downdrafts that descend to the ground, often associated with thunderstorms (Figure 2), and low level wind shear is defined as a sudden change in wind direction and speed occurring near the surface [21].)

Figure 1. The crash of Delta Flight 191 (US Govt. image, http://oea.larc.nasa.gov/trailblazer/SP-4216/toc.html)

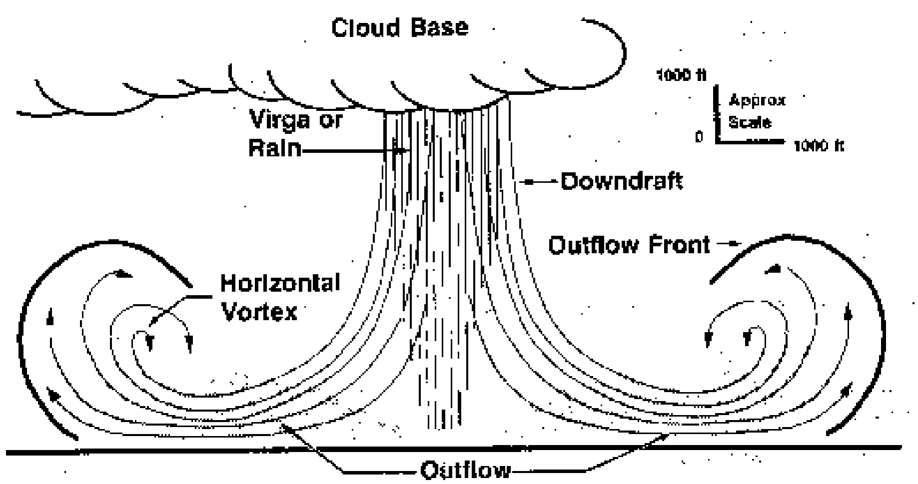


Figure 2. Microburst diagram (US Govt. image, http://oea.larc.nasa.gov/trailblazer/SP-4216/toc.html)

Part of what makes microbursts so deadly is that they are unexpected. They are characterized by a rapid updraft followed by an extreme downdraft. The problem is that when pilots encounter the updraft, they reduce the throttle to compensate; then when they hit the severe downdraft, the time it takes the pilot to react and increase throttle, and then for the engines to spool up, may not be sufficient to prevent the aircraft from hitting the ground (Figure 3). It has been shown that providing pilots with only a few seconds of warning before flying into a microburst can be sufficient to prevent accidents [126].

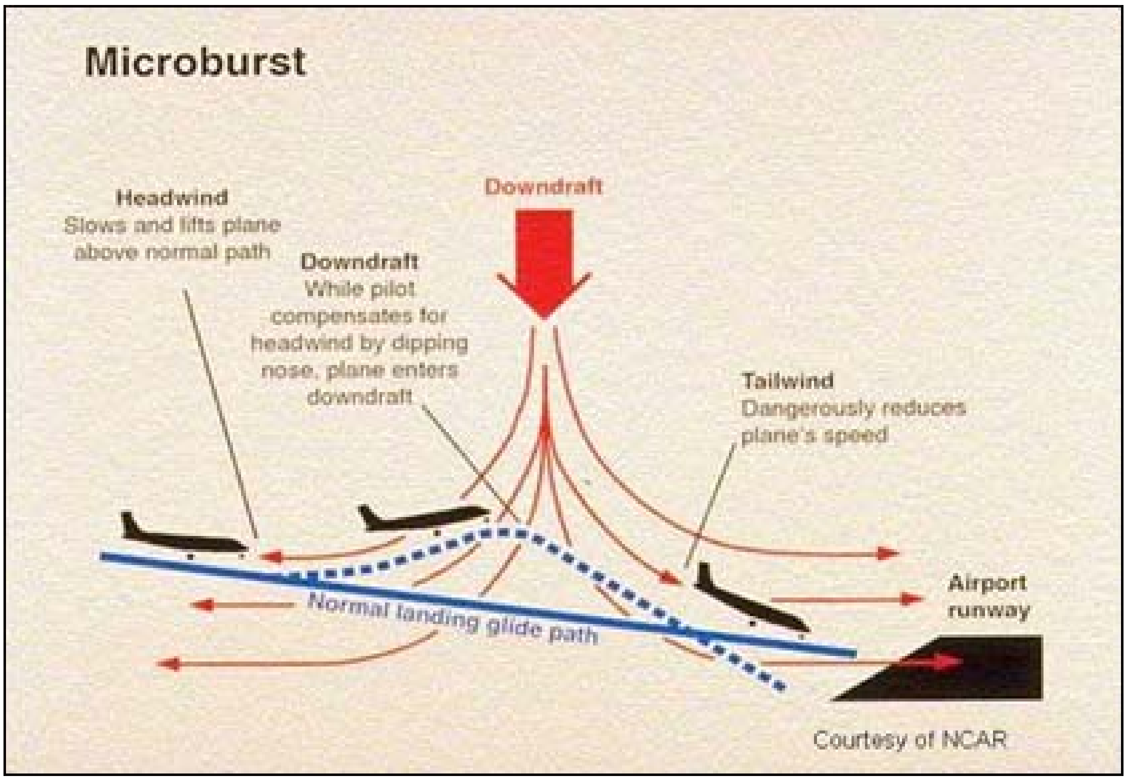


Figure 3. Why microbursts are dangerous to landing aircraft (US Govt. image, http://www.ncar.ucar.edu/)

Airflow hazards are challenging to detect simply because air is invisible. Pilots cannot discern airflow patterns unless the air happens to pick up dust, smoke or other aerosols visible to the human eye. Being thus unable to detect a factor of potentially great importance to them, pilots learn to use their intuition concerning airflow over obstacles near their takeoff or landing sites, and they learn to pick up visual cues from the surrounding area. However, airflow-related accidents still occur. Providing additional warning of airflow hazards could be of major benefit to aviation safety. (As a fixed-wing test pilot, airshow pilot, and flight instructor myself, with over 5,000 logged cockpit hours, I know from personal experience that before every approach it is important to scrutinize the landing zone for clues about the state of the winds over the runway.)

The following series of frames from two accident videos show graphically how airflow hazards can be implicated in aircraft accidents. The first video clip shows an H-46 dual-rotor helicopter attempting to land on a ship (Figure 4), (Figure 5), (Figure 6), (Figure 7), (Figure 8), (Figure 9), and (Figure 10).

Figure 4. H-46 dual-rotor helicopter approaching ship (all 7 frames are US Govt. images, courtesy K. Long)

Figure 5. Helicopter approach becomes slightly low as it nears ship

Figure 6. Helicopter landing gear does not clear ship deck

Figure 7. Landing gear becomes entangled in net

Figure 8. Pilot attempts to pull up, but helicopter enters dynamic rollover

Figure 9. Helicopter cannot recover

Figure 10. Unfortunately, there were several fatalities in this accident

The second video clip is of a fixed-wing aircraft, a C-2A Greyhound, making an approach to an aircraft carrier. Fortunately, in this incident there were no fatalities. However, an expensive aircraft sustained a great deal of damage. In this incident, it was later discovered that the shipboard anemometer (wind sensor) was giving an erroneous reading, and there was a much larger crosswind component than was communicated to the pilot (Figure 11)(Figure 12)(Figure 13)(Figure 14)(Figure 15)(Figure 16).

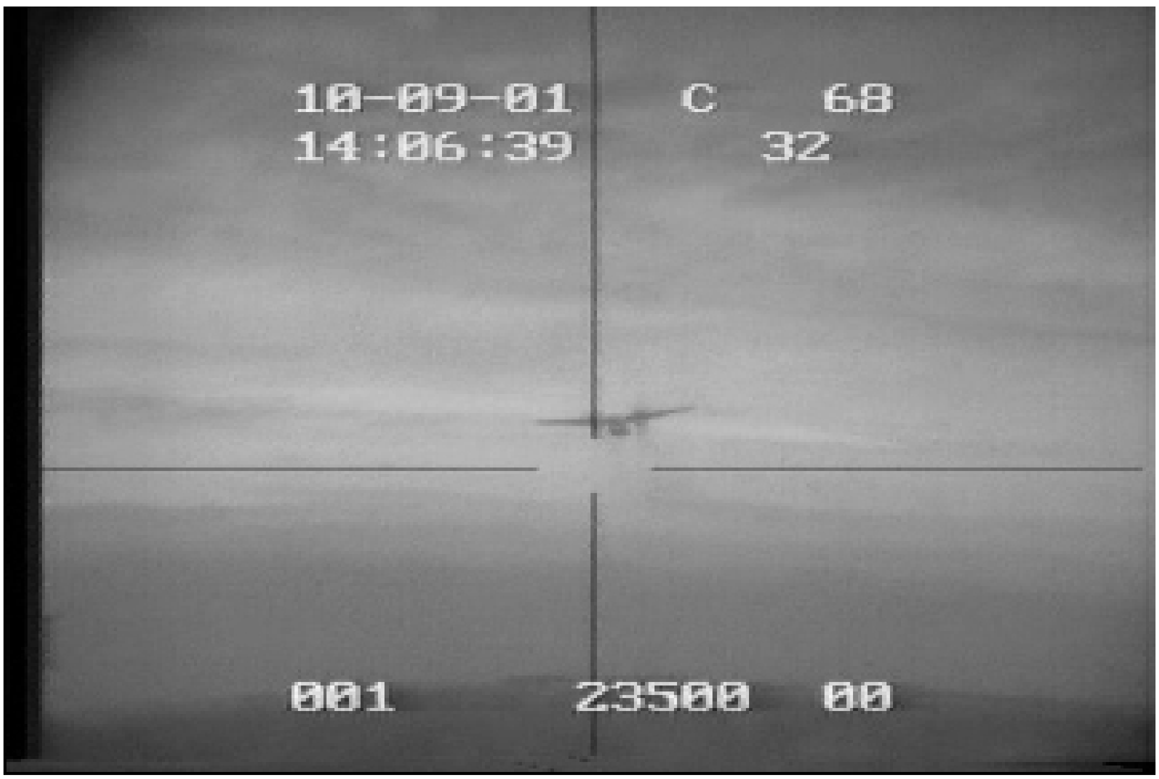


Figure 11. C-2A Greyhound is approaching for an aircraft carrier landing (all 6 frames are US Govt. images, courtesy K. Long)

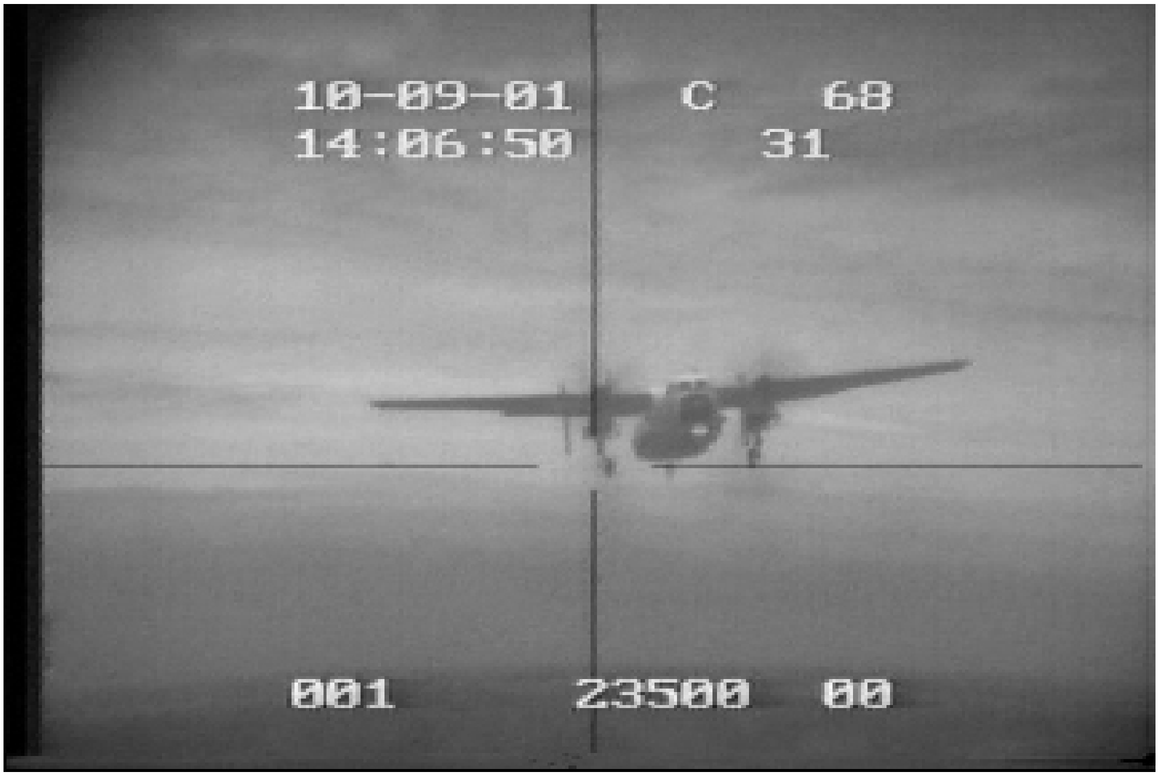


Figure 12. Aircraft begins to drift slightly left of centerline

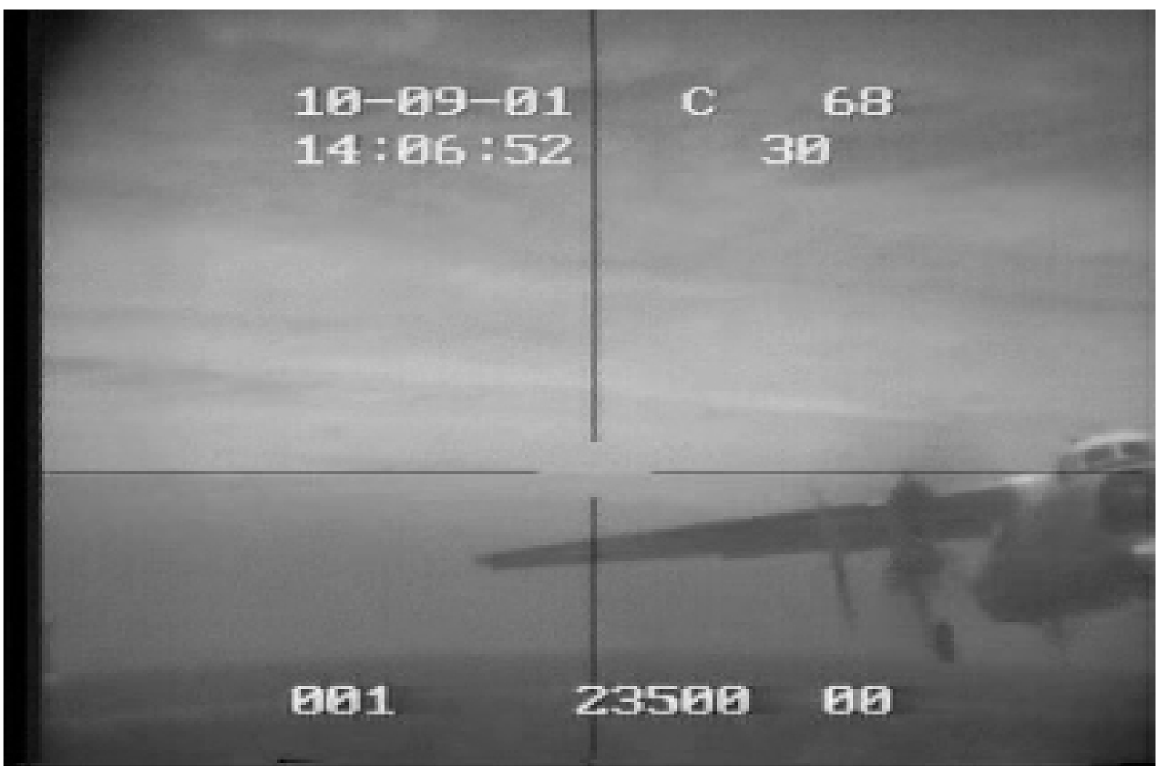


Figure 13. Aircraft deviates well left of centerline due to unrecognized crosswind

Figure 14. Aircraft lands on left edge of carrier runway

Figure 15. Aircraft landing gear slips off deck edge because pilot cannot compensate for crosswind

Figure 16. End result: an expensive and embarrassing accident

1.3 Focus on Helicopter Pilots

Although the risk of airflow hazards exists for all pilots in all aircraft, for our research we chose to focus on helicopter operations, and specifically on helicopter landings on moving ships. There were several reasons for this choice.

Helicopters are especially vulnerable to airflow disturbances such as vortices, downdrafts, and turbulence from surrounding vegetation or structures (Figure 17); first, by the nature of the aerodynamic forces involved, and second, because helicopters are often called upon to operate into and out of confined areas or areas that naturally have disturbed airflow. For example, emergency search and rescue may have to operate in mountainous areas and small clearings surrounded by vegetation (Figure 18) and cliffs with frequent high winds. Helicopters also must land on urban rooftops, offshore oil platforms, or on the decks of ships. A device for detecting airflow hazards therefore has a special utility for helicopter operations.

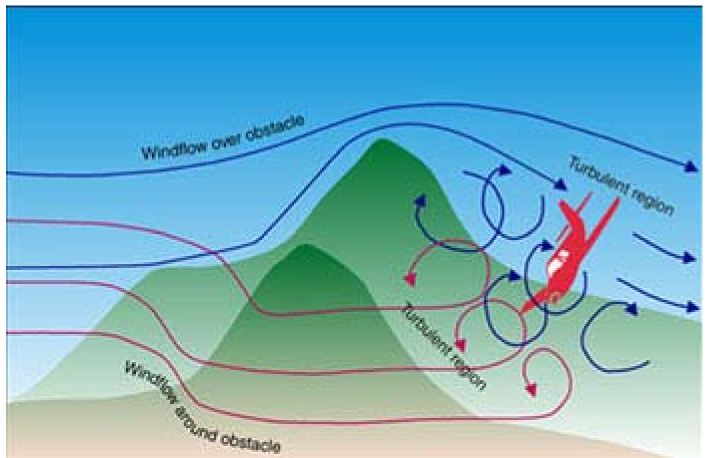


Figure 17. Turbulent flow and vortex formation on leeward side of obstacles (US Govt. image, http://www.nws.noaa.gov)

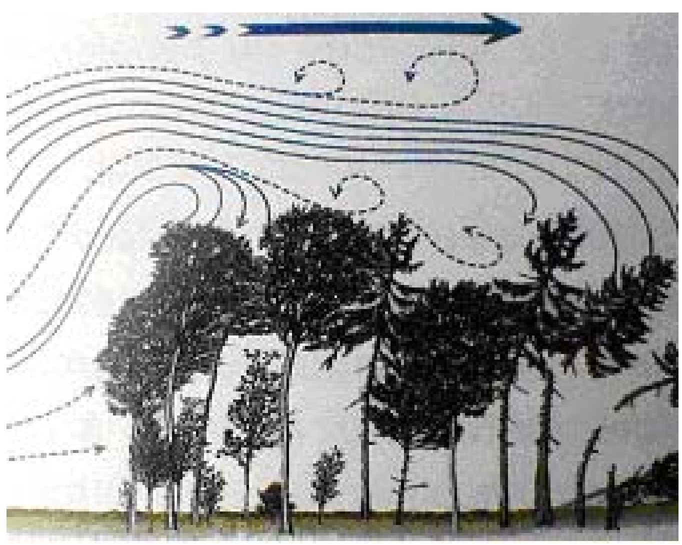


Figure 18. Turbulent airflow over vegetation (US Govt. image, http://www.nws.noaa.gov)

Operating a helicopter off a moving aircraft carrier is one of the most demanding tasks a helicopter pilot can face [135]. Because the ship is moving, its superstructure always generates disturbed airflow such as vortices and turbulence. In addition, high seas may cause extreme ship motion (Figure 19), and low visibility may degrade visual cues. The pilot must maneuver the helicopter within very tight tolerances to avoid striking ship structures or other aircraft. It is a task that demands the utmost concentration and skill from the pilot. A system that can deliver even an incremental amount of assistance to the pilot in this high-demand environment could have a significant impact on safety.

Figure 19. Helicopters landing on shipboard have to contend with high levels of pitch and roll (photo by K. Long, US Govt. image, courtesy of K. Long)

Helicopter accidents and incidents that occur on shipboard each year range from incidents such as “tunnel strikes” (where certain wind conditions can cause a helicopter’s rotor blades to spin out of control, damaging the fuselage of the helicopter) to fatal accidents. There have been over 120 tunnel strikes since the 1960s, causing damage ranging from $50K to over $1M per incident [69]. Analysis of these accidents and incidents frequently finds them to have been caused by unseen airflow hazards where the pilot and ground crew were initially unaware of the danger and the pilot was unable to react in time [35]. Presenting the appropriate information to the pilot or flight deck air boss (shipboard air traffic controller) in advance of the hazard encounter, therefore, could reduce or prevent such accidents.

Finally, because shipboard rotorcraft operations are such a demanding environment, the area is very well studied. The Navy has compiled significant amounts of data from shipboard flight tests, wind tunnel tests, and computational fluid dynamics computations studying the airflow around moving ships of all types, and how the airwake changes when helicopters of different makes and models land on the ships. The available data is thus sufficient to support a study on how better to present that data to the pilot.

1.4 New Sensor Technology

New advances in sensor technology such as Doppler lidar [31, 80] and other techniques are leading to the development of aircraft-based sensors which can collect large amounts of airflow velocity data in real time. Lidar is essentially laser radar (Figure 20). A transmitter sends out light, which bounces off the target aerosols or air molecules, and then a receiver collects the scattered light. Lidar systems are discussed in more detail in Chapter 3.

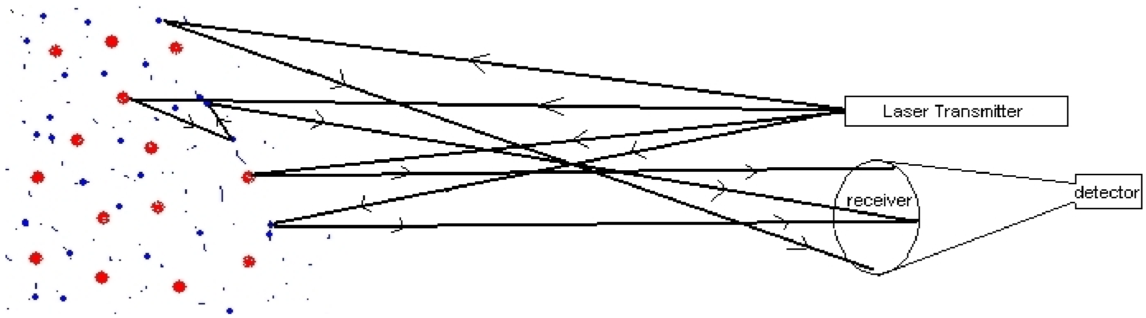


Figure 20. Lidar schematic (US Govt. image, http://www.ghcc.msfc.nasa.gov/sparcle/sparcle_tutorial.html)

Within a few years, it is likely that aircraft-mounted hardware will be available that can reliably scan the area a few hundred feet ahead of the aircraft and sample air particle vector velocities with precision of one foot or less [6, 53]. With the development of such devices, onboard detection systems that can convey detailed, specific information about airflow hazards to pilots in real time become a possibility. Such a system requires an interface that can present large amounts of data to the pilot in a comprehensive manner in real time, yet does not distract from the pilot's primary task of flying the aircraft. This is the information visualization task we attempt to address in this thesis: how does one best present, in real time, safety-critical information to a cognitively overloaded user?

1.5 Dissertation Outline

The remainder of this dissertation is structured as follows. In Chapter 2, we discuss relevant prior work. Chapter 3 discusses the low-fidelity prototype usability study in detail. Chapter 4 presents the design and implementation of our system in a high-fidelity rotorcraft flight simulator, and gives the experiment setup of the flight simulation study, and the results of the study. Finally, Chapter 5 discusses our conclusions and gives ideas for further work.

The final chapter is followed by appendices that contain scripts and materials from our usability studies, and finally, the references.

Chapter 2 ■

Related Work

Our research into airflow hazard visualization systems draws upon elements from multiple disparate disciplines, including scientific visualization, human factors in aviation, aviation displays, and US Navy shipboard rotorcraft operations. Each of these fields is a mature research area where significant bodies of research have been produced over decades. It is beyond the scope of this thesis to cover all the research accomplished in each of these areas. Instead, we focus on key findings that relate to the process of our research on the topic of airflow hazard visualization. In this section, we summarize some of the major developments in each of the above areas that have relevance to our research topic.

2.1 Human Factors in Aviation

Human factors in aviation is a large, mature field, almost as old as aviation itself. Ever since humans began creating flying machines, they have realized the importance of the human-machine interface. In fact, human factors in aviation have been studied since the Wright brothers first flew a powered aircraft in 1903. Orville and Wilbur Wright not only implemented levers so that a human could control the aircraft and tested them in a simple wind tunnel, they also developed simple instruments such as an angle-of-attack sensor (so the pilot could see how close the wing was to a stall while flying) and an automatic stabilizer [74].

"Human factors" is considered a branch of psychology and cognitive science, and includes all aspects of human interaction with machines.

Much of the human factors in aviation literature deals with "human factors problems," usually perceived as problems with humans being error-prone and therefore likely to do themselves in when placed in a dangerous situation such as an aircraft cockpit. In fact, one definition of human factors in aviation was "the personal and professional concerns that interfere with an aviator's ability to fly safely and effectively" [73]. This somewhat archaic view perhaps stems from the field's roots in the early days of aviation, when the dominant worldview was that humans were fallible, and in an interaction between human and machine, an error was almost seen as ultimately the fault of the human.

However, in recent decades this view has been changing. More recently we see less disparaging, more neutral definitions of human factors in aviation, such as "the study of how pilot performance is influenced by such issues as the design of cockpits, the function of the organs of the body, the effects of emotions, and the interaction and communication with the other participants of the aviation community, such as other crew members and air traffic control personnel" [112].

The field of human factors in aviation today encompasses psychological aspects of pilot performance as well as physiological and other issues [39, 42], and is an area of study that has yielded many interesting applications to areas other than aviation.

For example, Fitts' classic work [36] in the years after World War II discussed sources of pilot error such as slips of the hand between throttle and landing gear levers. Fitts' law, which predicts the time required for a human hand to move from a starting position to a final target area, has been widely applied in the HCI field and extended to areas such as mouse movement and other pointing devices.

2.1.1 Cockpit Automation

With the introduction of special-purpose and general-purpose computers into the aircraft cockpit, much study has been done of the interaction between pilots and automated systems. Wiener and Curry's seminal study in 1980 on flight-deck automation [133] discussed many of the issues that are still relevant today.

In recent years, as highly automated systems have become more prevalent in all aspects of human life, they have become essential to the operation of the modern jet cockpit. As computers have become faster, cheaper, and more powerful, the potential for both upside and downside of human-computer interaction in the cockpit has exploded. Early generations of autopilots, for example, were designed without much usability testing. Aviation experts learned the hard way that seemingly small glitches in an interface can have deadly consequences. It now appears that the famous crash of Korean Air Lines Flight 007 may have had its root cause in the lack of a tiny light, a mode annunciator in the autopilot [29]. There have been many aviation accidents attributable to problems with human-computer interaction in the cockpit [11]. As a result, it is generally understood in the aviation industry that this is an important research area, and the fields of human-computer interaction and human factors in aviation are showing more overlap in recent years than historically.

2.1.2 FAA Regulations Governing Cockpit Automation

Evidence that the view of human factors in the cockpit is changing includes changes in the ponderous legal system governing aviation. Human factors in aviation experts have recently convinced the Federal Aviation Administration (FAA) to include a formal usability evaluation in the official process for certifying hardware and software for the aircraft cockpit [99]. Formal usability studies are being undertaken of critical cockpit devices such as the Flight Management System (FMS). (Such studies have documented that one of the most common pilot comments when dealing with this system is, "What's it doing now?" [99]).

2.1.3 Human-Centered Aircraft Automation

Billings introduced the concept of "Human-Centered Aircraft Automation" in 1991 as "automation designed to work cooperatively with human operators in the pursuit of stated objectives" [10]. One of the important concepts Billings stressed in his work is that the computer interface should give the user sufficient feedback even when the machine is working correctly, not just when it has failed, so that the human can monitor it successfully. Additionally, information overload in the cockpit is a danger that may lead to channeling of attention and failure to perceive relevant information.

Billings stressed the importance of designing cockpit interfaces to assist and augment the human pilot, because human operators can cope with situations not envisioned by aircraft system designers and thus provide a degree of safety and flexibility to the overall system that a purely automated system cannot.

2.1.4 Studies of Attention in the Cockpit

There is a large body of work concerning human factors in the cockpit, including the study of attention and cockpit visual displays [8, 32, 33, 59, 90, 94, 111, 128, 129, 131, 132]. We touch very briefly on a few relevant papers.

In aviation, there has been a great deal of research performed with the goal of understanding how humans can process a large amount of input data to arrive at the appropriate conclusions. The term commonly used for pilots making sense of the environment around them is "situation awareness" (SA). More formally, situation awareness has been defined as "an internalized mental model of the current state of the operator's environment" [32]. The study of situation awareness has been formalized in the aviation industry. Situation awareness can be classified into three levels [33]. Level 1 SA (perception) deals with the perception of objects within the environment. Level 2 SA (understanding) refers to the comprehension of the meaning of those objects. Finally, level 3 SA (prediction) refers to an understanding of what will happen in the system in near future.

Each of these levels of situation awareness builds upon the one before. For example, a pilot cannot realize the risk posed by an airflow hazard in his or her path (Level 2 SA) if the hazard is not perceived by the pilot (Level 1 SA).

2.1.5 Studies of Head-Up Displays (HUDs)

Head-up displays (HUDs) provide flight information and guidance to the pilot on a forward field-of-view transparent screen (Figure 21). They have been well studied for use in aviation since they were first developed in the 1950s [88]. Although HUDs have been shown to improve pilot performance related to measures displayed on the HUD, studies have shown that pilot perception of unexpected events is degraded [88, 132]. For example, pilots perform better at maintaining airspeed if it is displayed on a HUD versus on a conventional head-down display. However, they will not perform as well if the task is detecting runway incursions, probably because their attention is captured by the compelling display on the HUD (cognitive tunneling). This difference is decreased if runway conflicts are depicted on the HUD itself (Figure 22) [5, 88, 90].

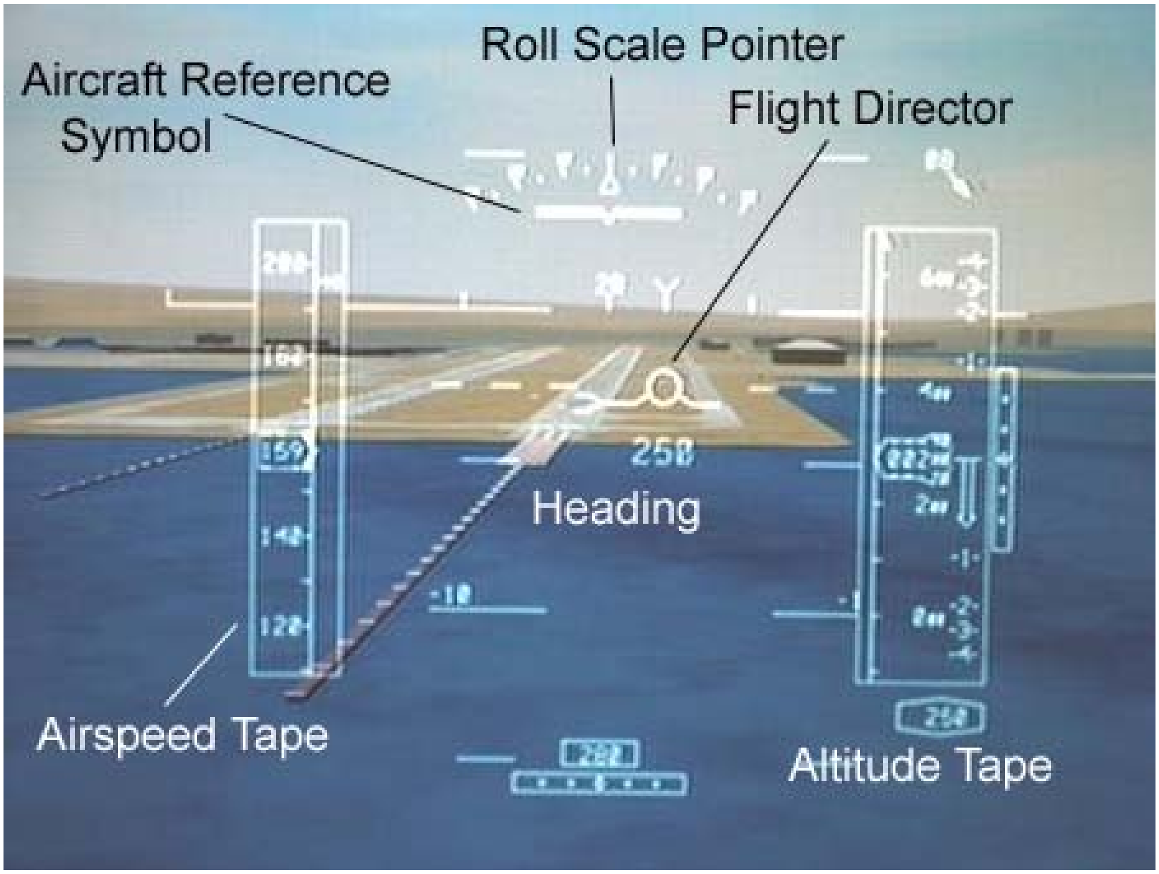


Figure 21. An example of HUD symbology (US Govt. image, courtesy of W. Holforty, labels added by C. Aragon)

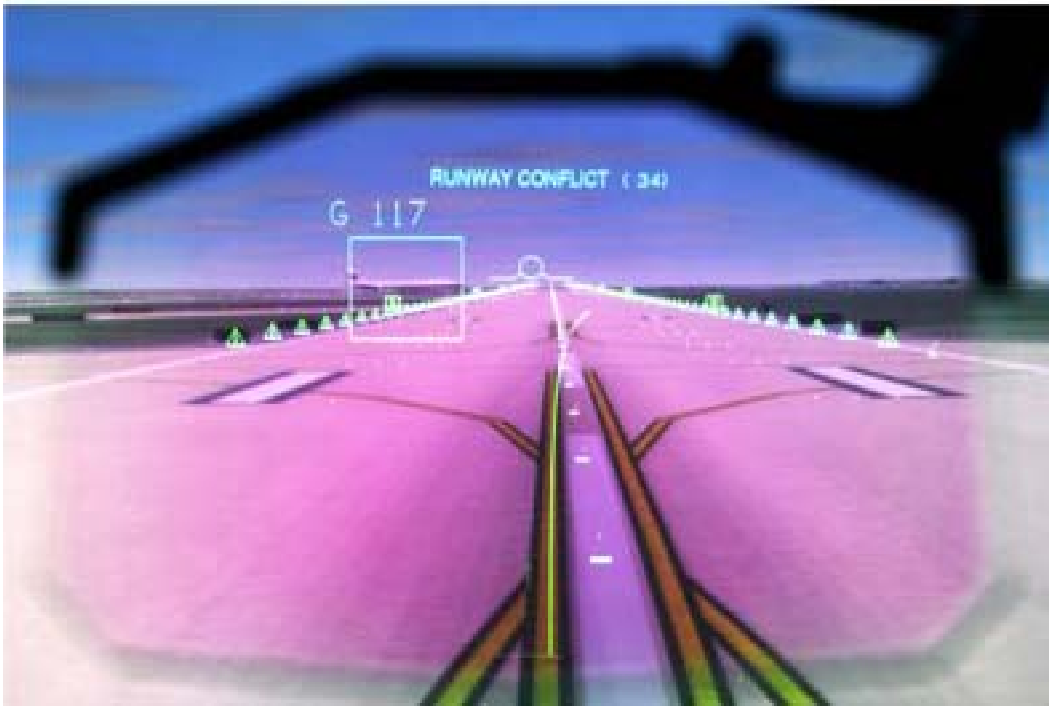


Figure 22. Synthetic vision on a head-up display: pilot advisory of runway conflict (US Govt. image, http://www.larc.nasa.gov)

Studies have been performed to examine this degradation in pilot performance, and McCann [66, 67] has shown that using "scene-linked" symbology (objects that appear to be present in the real world and are not just "painted" on the surface of the HUD) mitigates this decrease in pilot detection of unexpected events.

Although none of the work was specifically directed to optimizing airflow hazard display, the analyses of how attention is divided in the cockpit and the HUD usability studies informed our system design, as will be described in more detail in Chapter 3.

2.2 Aviation Displays

It has long been recognized that applying developing technology to improve aviation displays might enhance aviation safety. Since 1929, when Jimmy Doolittle became the first pilot to fly an aircraft solely by reference to flight instruments [12], ongoing efforts have been made to provide pilots with information that they are unable to see out the window.

In prior work, the focus of aviation displays and instruments has usually been on displaying terrain that may be hidden by clouds, navigation aids, and displays of adverse weather.

2.2.1 Synthetic Vision Systems

"Synthetic vision" has been defined as the technology necessary to provide "all-weather visibility" to the pilot [17]. In 1999, NASA Langley Research Center began a project to research the development and integration of such technology into aircraft cockpits. Langley's Prinzel has enunciated this goal as [89], "The NASA synthetic vision system will integrate … navigation displays; runway incursion prevention technologies; database integrity monitoring equipment; enhanced vision sensors; taxi navigation displays; 'highway in the sky' tunnels and guidance; and advanced communication, navigation, and surveillance technologies."

Synthetic vision systems have been shown to reduce aircraft accidents, especially "controlled flight into terrain" which may occur when visibility outside the cockpit is low, for example when the pilot is flying in fog [40].

There has been a significant amount of work in the area of synthetic vision systems technology development [3, 5, 7, 17, 19, 40, 49, 54, 89, 90, 103, 108, 111, 117]. However, the focus has been primarily on terrain visualization and the display of navigational aids to the pilot. Nevertheless, the usability studies on synthetic vision aircraft displays guided us in our design of our airflow hazard display system, and it is interesting to consider how our display might be integrated into a full synthetic vision system. Recent work on the integration of sensor data into synthetic vision systems [2, 95, 110, 111, 130] highlights technical challenges in this field.

2.2.1.1 Augmented Reality Displays

An airflow hazard visualization system can be considered as an example of "augmented reality." Augmented reality has been variously defined as "augmenting natural feedback to the operator with simulated cues" or "a form of virtual reality where the participant's head-mounted display is transparent, allowing a clear view of the real world [71, 72]. HUD technology (which was discussed earlier in section 2.1.5), as used in military aviation displays, is a relatively mature use of this technology; more recently, a growing body of research has focused on wearable systems, such as those which can be worn by an individual operating in a city. When computer-generated imagery is overlaid on real objects, the technical challenges involved, including information filtering, spatial registration, and how to combine visible and obscured information, are considerable [38, 51, 52]. Much of this branch of the augmented-reality research focuses on non-aviation areas; however, developments in this field could benefit and improve the quality of our display.

2.2.2 Weather Prediction and Visualization

Research into technologies to inform pilots that they are about to encounter dangerous weather conditions has been conducted in the aviation industry for decades. However, the focus has been primarily on detecting the phenomena, rather than on how to communicate the detected information to the pilot. In this section we discuss weather visualization projects including NASA's AWIN, TPAWS and AWE (Figure 23) [14, 58, 96, 102], and studies of turbulence detection and prediction [107].

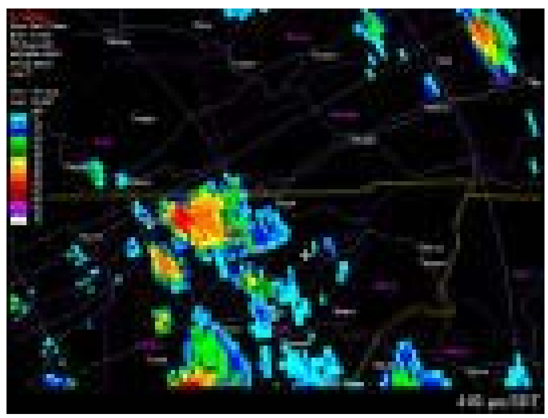


Figure 23. Typical weather radar imagery (color-coded by intensity of echoes) (US Govt. image, http://nix.nasa.gov)

2.2.2.1 NASA AWIN

NASA's Aircraft Weather Information (AWIN) [77] program is an element of the Weather Accident Prevention (WxAP) project [79], which in turn is part of the NASA Aviation Safety and Security Program (AvSSP) [76]. Based at NASA Langley Research Center, this program fosters research into the provision of real-time aviation weather to the aircraft cockpit. The work includes usability studies that have been conducted on data-linked, real-time aviation weather displays [58, 96].

These studies have demonstrated the importance of including usability considerations when designing a graphical weather information system (GWIS). Although pilots are uniformly enthusiastic about the idea of receiving graphical weather information in the cockpit, a GWIS, if not designed properly, may increase pilot workload but not improve pilot decision-making with respect to weather [137]. During in-flight studies conducted under the NASA AWIN program, a number of safety-critical GWIS features have emerged, including prominently displaying the age of the weather data, and placing a knob for brightness control on the display [58].

2.2.2.2 NASA TPAWS

NASA's Turbulence Prediction and Warning Systems (TPAWS) [78] program develops technologies to provide airline pilots real-time information about enroute atmospheric turbulence at least thirty seconds in advance. This program focuses on detection and integration of a warning system into existing airliner avionics. Flight testing is ongoing [14].

2.2.2.3 Microburst Detection

It has been known since the 1980s that weather-related airflow phenomena such as microbursts and low level wind shear (occurring near the ground) have been responsible for airliner accidents [118]. As a result, a great deal of work has been done to detect, predict, and display this type of information to the pilot [120, 126]. There are commercially available aircraft-based, forward-looking microwave radar and lidar systems that can detect microbursts and wind shear. However, rather than designing new displays to optimally present the new data, the developers emphasized reduced time to commercial deployment by integrating the information into existing cockpit displays. Accordingly, no usability studies were focused strictly on the display itself or on whether a three-dimensional head-up display would be more helpful in presenting hazard information to the pilot.

2.2.2.4 Other Weather Visualization Systems

2.2.2.4.1 Aviation Weather Environment (AWE)

In 2002, Spirkovska and Lodha [102] developed an interactive weather visualization system that was aimed at the general aviation pilot. The system was developed based on pilot feedback from usability studies, and included a direct manipulation graphical interface and a speech-based interface to improve pilot situational awareness of weather data. The interface was two-dimensional, and based on existing aviation weather charts and products.

2.2.3 Flight-Deck Display of Neighboring Aircraft Wake Vortices

In 2003, Holforty [45] developed a system for wake vortex prediction and display. (As an aircraft passes through the air, it leaves a trail called wake vortices that can be hazardous to following aircraft.) The system provided wake vortex visualization to pilots on a head-down display, during the enroute (least demanding) phase of flight. The focus of this work was more on the prediction of the location of the wake, and less on the usability of the display, but it was the first study that attempted to display a three-dimensional visualization of any type of airflow hazard to pilots.

Holforty developed a predictive algorithm for the location of wake vortices and implemented it in a synthetic vision head-down display that enabled pilots to visualize the wakes of neighboring aircraft (Figure 24). The display was evaluated under both simulated and actual flight conditions. Pilots reported a significant increase in their awareness of the position of the wake vortices, and the predictive algorithm was experimentally verified during the flight test.

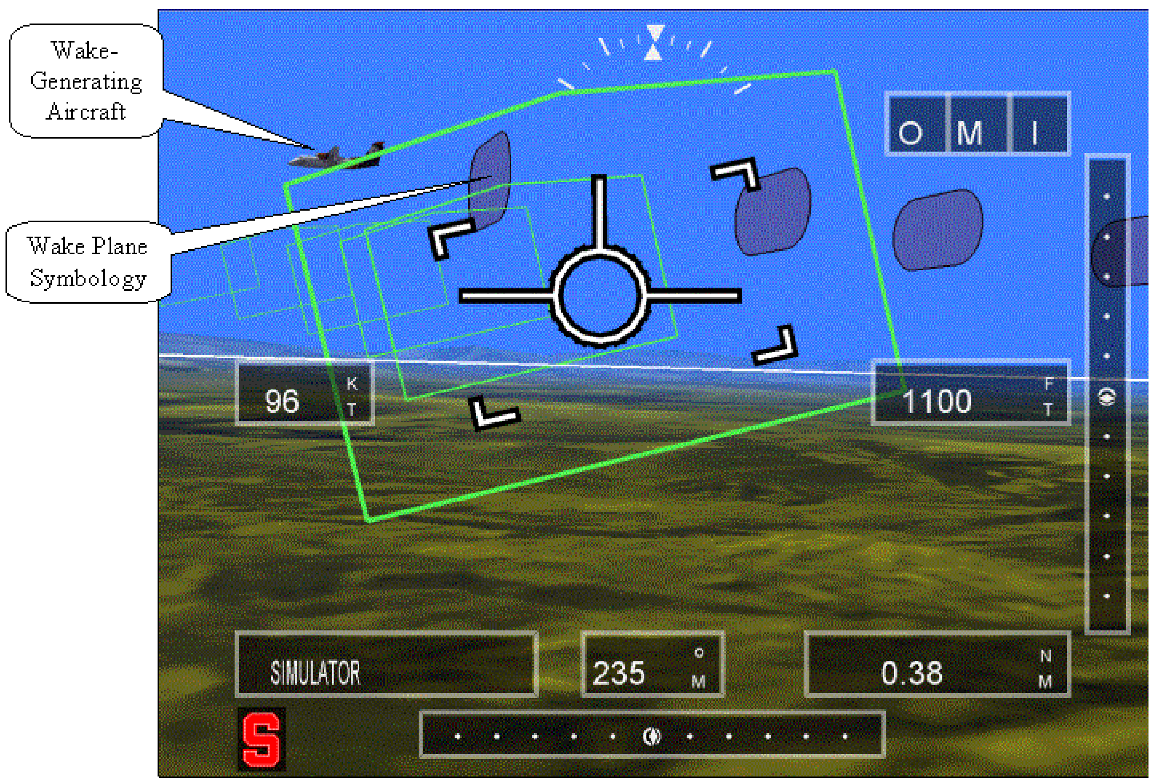


Figure 24. Holforty's wake turbulence cockpit display (US Govt. image, courtesy of W. Holforty)

2.3 Information Visualization

Information visualization is defined by Spence [101] as "the process of forming a mental model of data, thereby gaining insight into that data." Spence and Card et al. [20], both authors of textbooks on information visualization, each credit Sir Edward Playfair with the origin, in 1786, of the idea of "data graphics" [20, 101], or the visual representation of abstract data. Card et al. also note that in 1967, Bertin, a French cartographer, published a theory on graphics which has had much influence on the field [9]. Another significant contributor to the field was Tufte [113-115], who published three books arguing for the meaningful use of graphics in representing data.

Information visualization is often distinguished from scientific visualization in that it deals with abstract data as opposed to physical data. We chose to use the term "information visualization" in the title of this thesis deliberately; our work lies on the border between the physical and the abstract. Although we are presenting a visualization of physical data to the pilot, the process of user-centered design led us to a highly stylized abstraction of the flow data. At the beginning of this project, we believed we would be working in scientific visualization. However, as our study proceeded, it became clear that in order to be effective, an abstract representation of the hazardous airflow, rather than a technically detailed flow visualization, was what pilots need.

2.4 Flow Visualization

Flow visualization is a broad area, and an important subfield of scientific visualization, where research spans many applications including aerodynamics, physics, weather simulation, and any area of study where fluids or gases are in three-dimensional motion and researchers are concerned with understanding the flow. Flow visualization systems often consist of detailed imagery of two- and three-dimensional airflow patterns, both static and dynamic, steady and unsteady, all designed to help scientists or engineers perceive and interpret — and analyze at length — a particular instance of a fluid flow. Additionally, visualizations may be static or animated; and if animated, the type of animation can be chosen for a particular objective, such as to minimize compute time (e.g. color table animation) or to maximize detail presentation.

The images produced by many of these techniques are unquestionably complex and beautiful. They often take many hours of compute time to produce, and the results give the viewer an increased understanding of the complexities and often counterintuitive nature of fluid flow around obstacles. Although we did not end up utilizing this type of flow visualization in our cockpit display, we give descriptions of the major techniques because of their relevance to the airflow data we are studying, and as a means of comparing and contrasting the imagery prevalent in this field with our final display.

2.4.1 Computational Flow Visualization Techniques

Flow visualization techniques can be broadly divided into two main subgroups: computational and experimental. Most of the research on flow visualization has been done on computational fluid dynamics (CFD) solutions; in these, because the data is computed rather than captured from sensors, it is relatively easier to access and visualize. However, the visualizations used in computational techniques are in many cases similar (at least in visual appearance) to those used in visualizing experimental flow data, so examples of a particular type can often be found in both fields.

Post [87] and Laramee [57] have proposed a taxonomy of flow visualization techniques. They focus on computational techniques; however, they note that computational visualizations often mimic experimental techniques. The classification divides the set of techniques into four main areas: direct, texture-based, geometric, and feature-based. We give brief examples of each below.

2.4.1.1 Direct Flow Visualization

Direct flow visualization techniques, often called global techniques because they are usually applied to the entire data set, typically do not involve much pre-processing of the data. Visualization cues such as arrows may be drawn over the data, or velocities may be color-coded. Examples are given in (Figure 25), (Figure 26), and (Figure 27). An additional example may be found in SRI's TerraVision, where two-dimensional arrows are overlaid in a three-dimensional scene (Figure 28). Among the advantages of using techniques such as these to visualize fluid flow are that compute time is minimized, the visualization cues are simple and easy to understand, and familiar domain symbology can be used. (For example, most pilots are well acquainted with wind arrows due to extensive experience with weather briefings. In order to receive a pilot's license, the Federal Aviation Regulations (FARs) mandate memorization of all the symbology used in weather charts.)

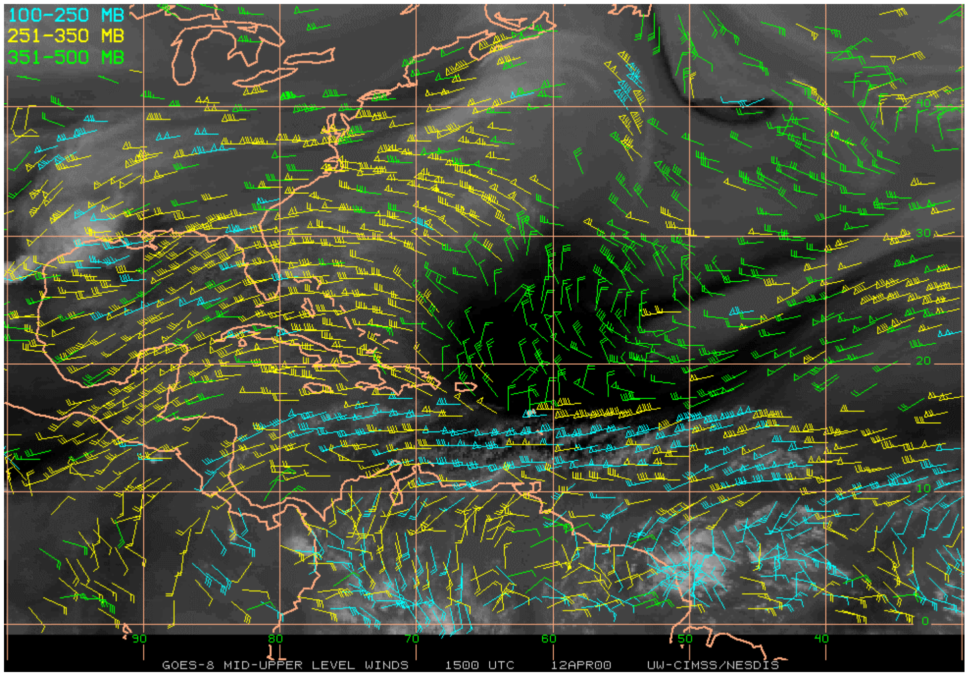


Figure 25. Example of direct flow visualization - wind arrows superimposed on satellite photo (US Govt. image, http://www.weather.noaa.gov)

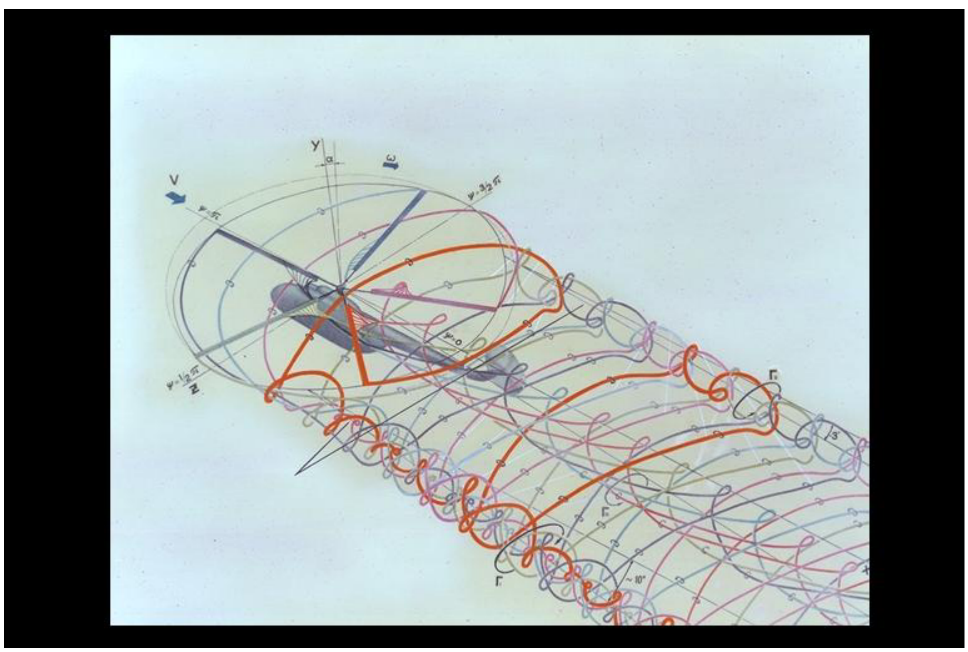


Figure 26. Example of direct flow visualization: rotor wake vortices (US Govt. image, http://ails.arc.nasa.gov/Images/Aeronautics/AC76-0585.5.html)

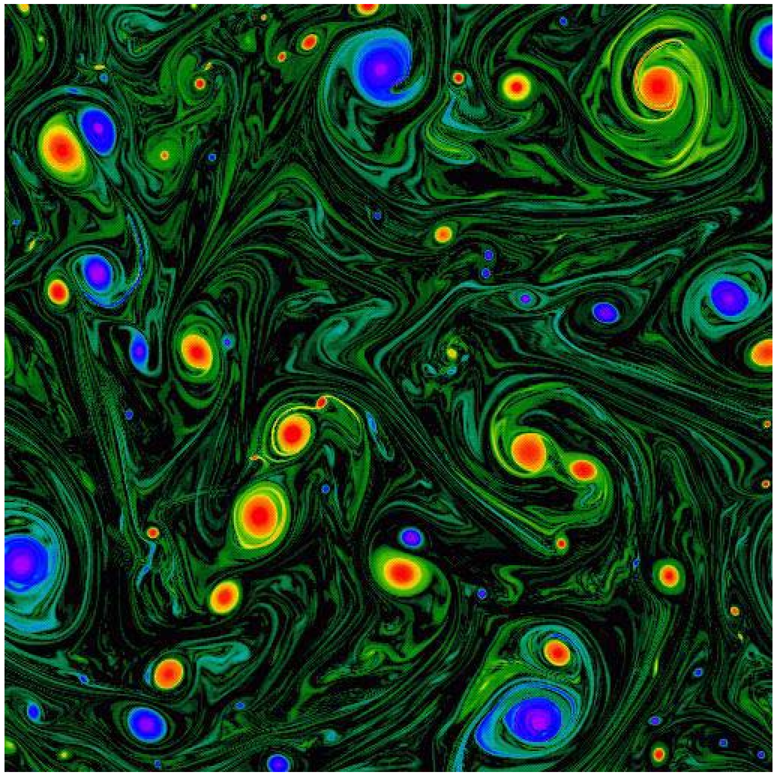


Figure 27. Example of direct flow visualization - 2D visualization of turbulence (color-coded by velocity) (US Govt. image, http://ails.arc.nasa.gov)

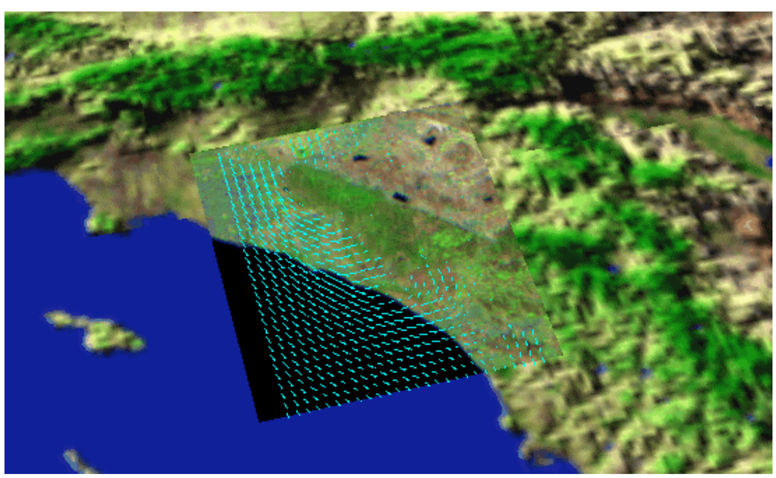


Figure 28. Example of direct flow visualization - 2D wind arrows computed by SRI's TerraVision (image courtesy of SRI International, http://www.ai.sri.com/TerraVision)

2.4.1.2 Texture-Based Visualization

These techniques often involve integrating the flow data to produce texture values, which are then visualized over a surface. Integration is a natural technique to apply because flow data is usually derivative information with respect to time, so it makes sense to attempt to generate features in the flow by integrating the data. To display the results, a textured pattern, where the texture values are filtered according to the flow vector at each location, is applied to the two-dimensional surface of a three-dimensional object.

Examples of texture-based flow visualization techniques include line-integral convolution (Figure 29), spot noise (Figure 30), texture advection, texture splats (Figure 31), and image-based flow visualization.

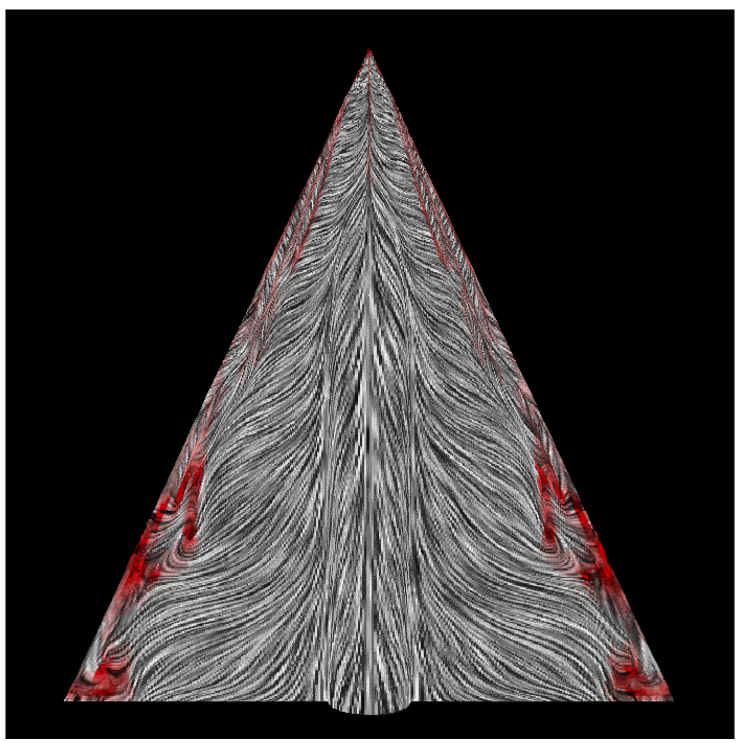


Figure 29. Example of texture-based flow visualization - Space shuttle flow depicted using line-integral convolution (LIC) (US Govt. image, http://www.nas.nasa.gov/Groups/VisTech)

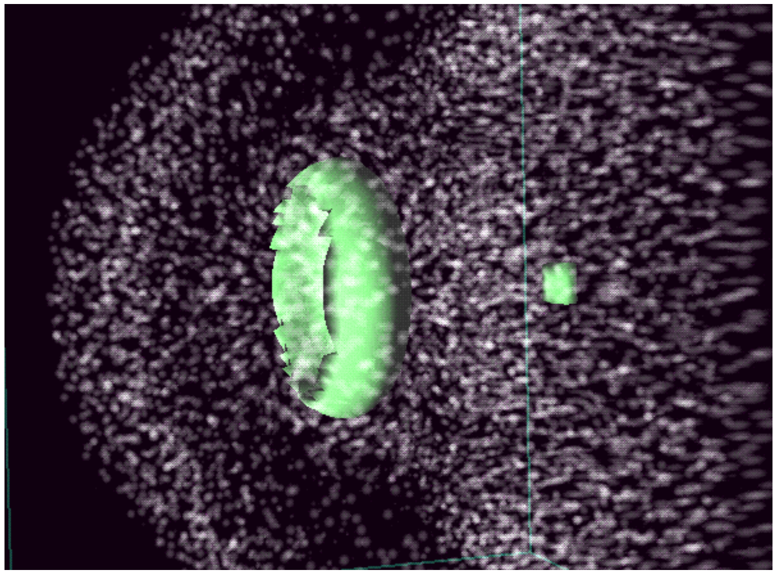


Figure 30. Example of texture-based visualization - spot noise flow visualization (US Govt. image, http://www.llnl.gov/graphics/gifs/spotKlein_600.gif)

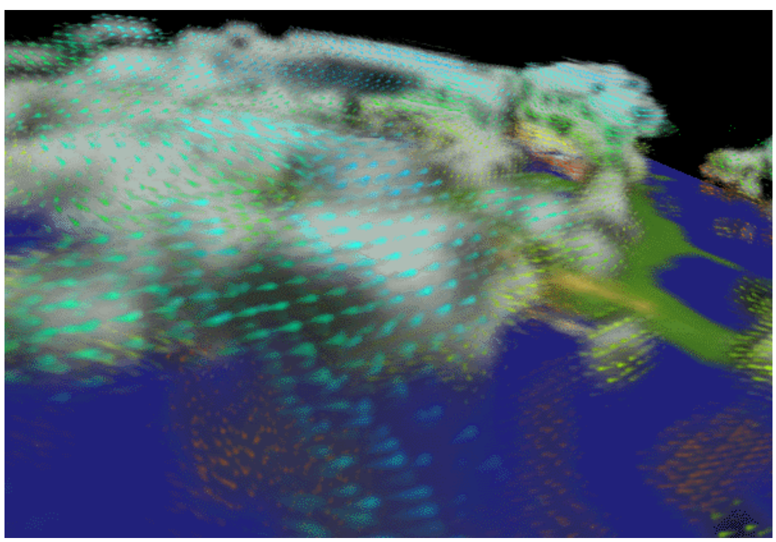


Figure 31. Example of texture-based visualization - Monochrome texture splats with colored textures show wind direction in North America (US Govt. image, http://www.llnl.gov/graphics/splats.html)

Line-integral convolution (LIC) was introduced by Cabral and Leedom [18]. The 2D vector field of flow data is convolved with a white noise texture in this technique. There have been many extensions of LIC [57], including for parallel computing, curvilinear grids, 3D volumes [46], multi-variate LIC [119], simulated dye injection [97], and for unsteady flow [98].

Spot noise, first introduced by Van Wijk [86, 125], involves generating a texture by distributing a set of intensity functions, or spots, over the flow field. Each spot visualizes a particle smeared over a small step in time in the direction of the local flow. This technique has also been extended in many different ways, such as enhanced spot noise [28] which allows the representation of high local velocity curvature, parallel algorithms for spot noise [25], the application of spot noise to unsteady flow [27] and turbulent flow [26].

Texture advection involves the animation of texture-mapped polygons with motion directed by the underlying vector field. These techniques include image-based flow visualization [124], moving textures [64], and 3D visualization [48].

Other texture-based techniques include texture splats (a 3D volume rendering visualization technique) [23], anisotropic diffusion (a technique from image analysis) [30], and Markov Random Field texture synthesis for steady flow [109], where textures are modified using techniques that produce streamline patterns.

2.4.1.3 Geometric Flow Visualization

With geometric flow visualization, the first processing step consists of extracting geometric objects from the flow data, which depict useful information contained in the vector field. Examples of this technique include streamlines (Figure 32) and contour lines (Figure 33) for the case of instantaneous flow [16] [104], and streaklines, timelines (Figure 34) [56], and flow volumes (Figure 35) [65] for unsteady flow. SRI's TerraVision (Figure 36) [116] also uses this technique for turbulence visualization and the visualization of airflow over terrain.

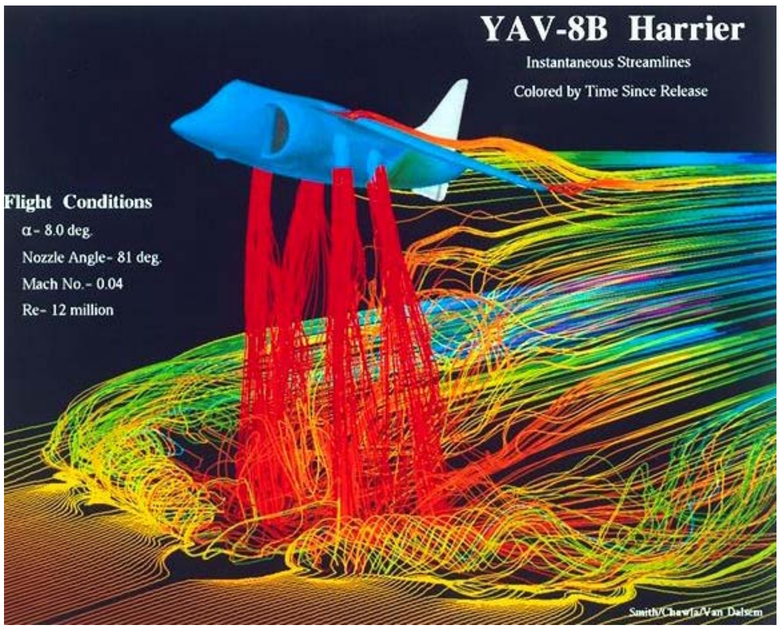


Figure 32. Example of geometric flow visualization: instantaneous streamlines (US Govt. image, http://www.nas.nasa.gov/Groups/VisTech)

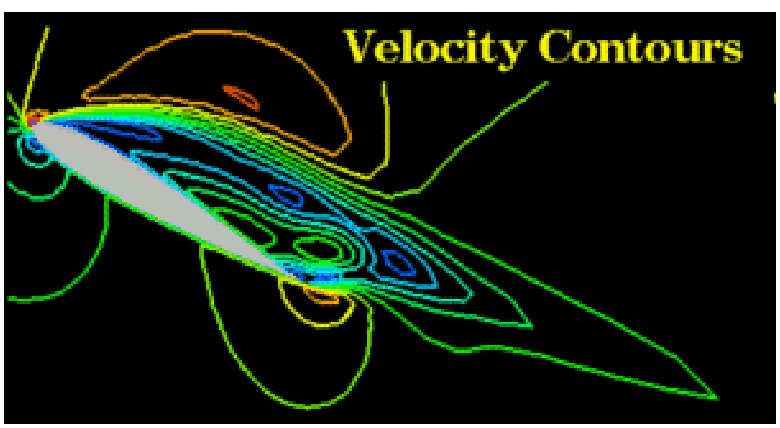


Figure 33. Example of geometric flow visualization - Velocity contours in 2D (US Govt. image, http://www.nas.nasa.gov/Groups/VisTech)

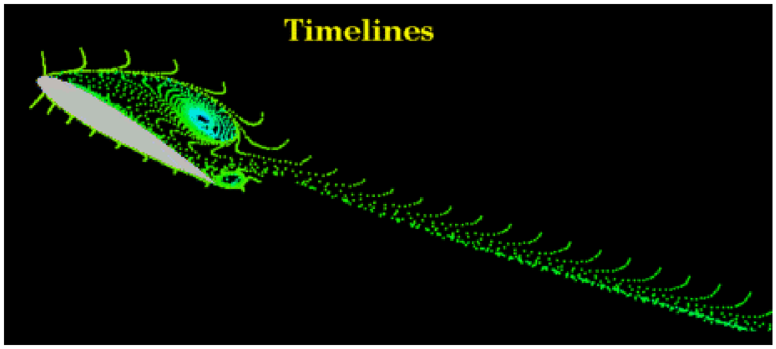


Figure 34. Example of geometric flow visualization - Timelines: unsteady flow visualization (US Govt. image, http://www.nas.nasa.gov/Groups/VisTech)

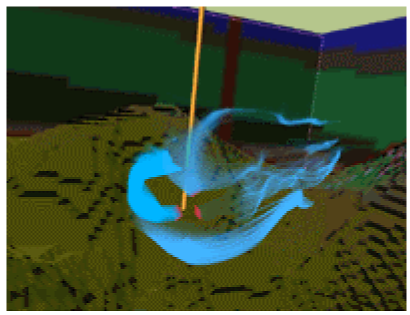


Figure 35. Example of geometric flow visualization - Flow volumes (US Govt. image, http://www.llnl.gov/graphics/flow.html)

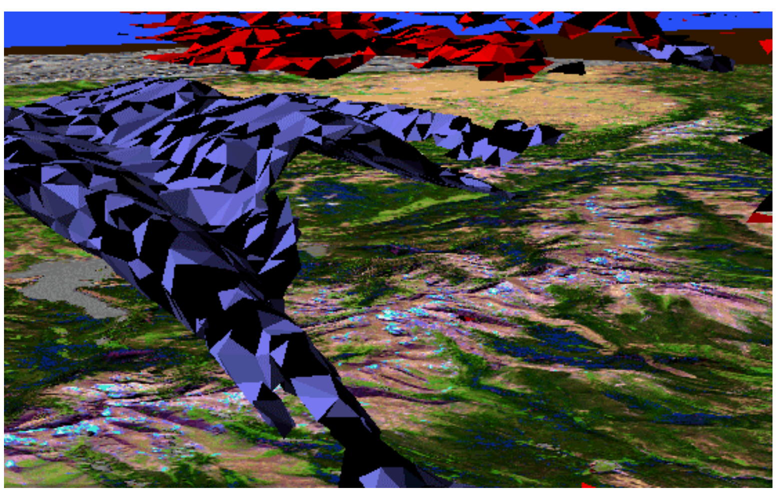


Figure 36. Example of geometric flow visualization - SRI's TerraVision: visualizing clear air turbulence (image courtesy of SRI International, http://www.ai.sri.com/TerraVision)

2.4.1.4 Feature-Based Visualization

In feature-based visualizations, key features of the underlying flow data set are first extracted. Then visualization is performed only on the subset of the data thus separated, allowing for a large speed-up in visualization compute time. Flow data set features may include vortices, shock waves (Figure 37), boundary layers, and other aerodynamic or fluid flow artifacts of interest to the researcher producing the visualization.

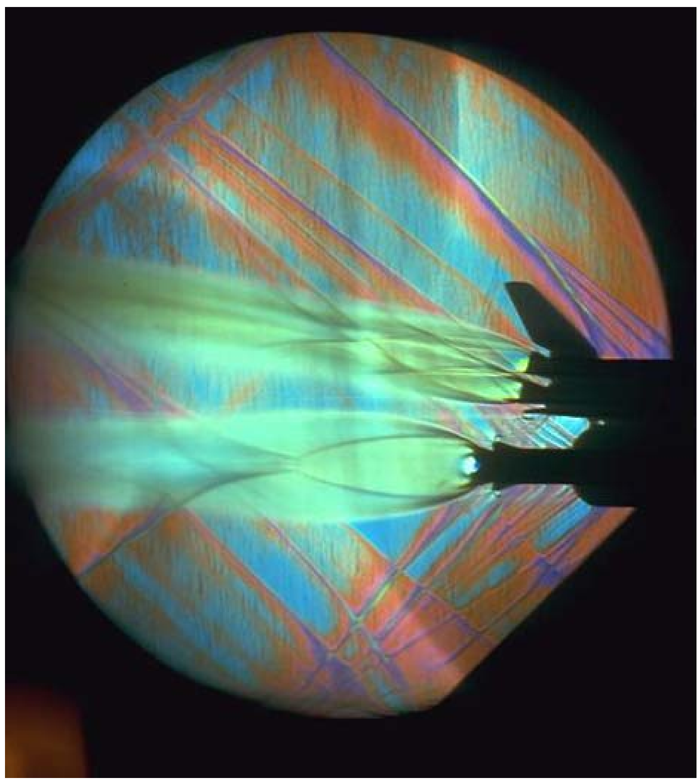


Figure 37. Example of feature-based flow visualization - Space shuttle shock waves (US Govt. image, http://www.nas.nasa.gov/Groups/VisTech)

Because this method scales well to very large data sets, it is a very popular technique. An example is image processing feature extraction, such as the topological analysis of 2D vector fields [44]. Another useful technique is feature extraction based on physical characteristics, such as the detection of swirling flow, developed by Sujudi and Haimes [106]. The algorithm uses the velocity gradient tensor to detect areas in the flow where a strong swirling flow is present. This algorithm works well at finding vortices in 3D flow when vorticity is strong.

Shock waves are aerodynamic phenomena characterized by discontinuities in physical quantities such as pressure, density, and velocity. They often occur as aircraft approach the speed of sound (Mach One). Detection of shock waves is comparable to edge detection in many ways. There have been many techniques developed for shock wave detection in two and three dimensions [62].

2.4.2 Experimental Flow Visualization

Experimental flow visualization refers to techniques used in wind tunnel tests, water channel tests, other physical simulations of flow, or real-world tests of airflow (Figure 38). Common techniques for experimental flow visualization include particle traces, dye injection, or Schlieren techniques (Figure 39) [123]. Aluminum dust in water, glass beads in glycerin, or smoke trails in air, can be photographed as the fluid flows past an obstacle. Such visualizations have been used for many years, with the purpose again being greater understanding of airflow or fluid flow around an object. It has been noted that computational and experimental flow techniques often present a similar appearance [57], perhaps due to the nature of the human visual system. It may be that researchers studying new methods of flow visualization look to their prior knowledge of visual flow in the world around them, such as smoke trails, dust devils, colored liquid, particles immersed in water, etc.

Figure 38. Example of experimental flow visualization - Wake vortex visualized by smoke and color enhancement (US Govt. image, http://www.larc.nasa.gov)

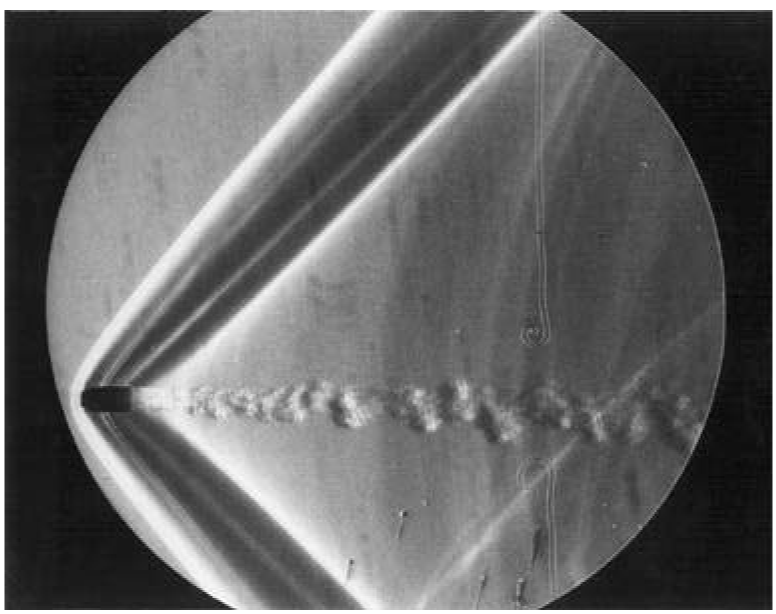


Figure 39. Example of experimental flow visualization - Schlieren photograph of a shock wave created by a bullet (photo by A. Davidhazy, reprinted with permission, http://www.rit.edu/~andpph/text-schlieren.html)

2.4.2.1 Particle Traces

As particles move in a fluid flow, they can be photographed with a slow shutter speed so that they leave traces on the resulting photograph. This technique yields useful information about the patterns in the flow [123].

2.4.2.2 Dye Injection

Fluorescine dye can be injected into a water channel and observed or photographed under black light. This technique has the advantage of being very simple and inexpensive to implement, in that almost any type of object can be coated with a waterproof coating and immersed in the water channel for study. In a recent test at NASA Ames Research Center, the airflow around a baseball was studied [60].

2.4.2.3 Schlieren Techniques

Schlieren, shadowgraph, and interferometric photography can detect density gradients in any transparent medium [24]. These techniques have been used for many years in experimental flow visualization [123]. In Schlieren photography, gradients in the transparent flow deflect light rays across a sharp edge, which makes visible patterns.

2.4.3 Usability Studies of Flow Visualization

However, while the intricacy and compelling aesthetic qualities of these images suggest their potential value to users, there have been very few user studies undertaken on scientific visualization. Laidlaw et al. [55] conducted a usability evaluation of different types of two-dimensional flow visualization techniques, asking viewers to find critical points in the flow and predict where a particle might end up. User error was higher than expected for all methods, indicating that there is room for improvement in this field, and that HCI techniques might be successfully applied to scientific visualization.

2.4.4 Flow Visualization for Pilots

At the beginning of this research project, there was an assumption that this work would center on determining the best type of animated flow visualization to convey the airflow data to the pilot. After a literature survey of the plethora of techniques of flow visualization, it appeared that the research plan would include presenting a variety of detailed, animated flow visualizations to helicopter pilots landing in disturbed air and observing their performance and reactions.

As a fixed-wing pilot myself, I had landed many times on runways where a dust devil or smoke trail gave away airflow information, and found it very helpful in planning my landing approach. It seemed logical to apply this idea to the design of the airflow hazard visualization system.

2.4.4.1 Human-Centered Design

However, one of the benefits of the human-centered design technique is that it prevents the researcher from traveling a false trail. Scientific and flow visualization are esthetically pleasing, and a designer may wish to produce a beautiful interface. However, although esthetics is undeniably an important consideration, in the fields of aviation safety or any other safety-critical applications, there are other more vital issues.

We initially investigated the use of flow visualization similar to these techniques described above. However, by applying HCI techniques to the problem, such as enlisting the feedback of domain experts in an early, interactive low-fidelity prototype, it quickly became apparent that such visualizations would not be appropriate in the type of situations we were studying. The pilots felt that classic flow visualization imagery was distracting and presented too much information. Their view was that the imagery was quite complex and not suitable for rapid glances during time-critical tasks. We describe the process we used to solicit pilot feedback, as well as the final choice of imagery for the hazard visualization system, in Chapter 3.

2.5 Helicopter Shipboard Operations

The US Navy has conducted shipboard rotorcraft operations since 1943, when a Sikorsky XR-4 landed aboard the SS Bunker Hill (Figure 40). Landing a helicopter on a moving ship deck is one of the most demanding tasks a pilot can face [135]. The pilot must land the helicopter within a very small area on a pitching and rolling deck without overstressing the landing gear, with the rotor blades often only a few feet from the ship superstructure. Frequently, the pilot must contend with low visibility due to poor weather, salt spray or nighttime operations. The ship superstructure always generates an airwake (turbulent flow) aft of the structure as it moves. In addition to these issues, aircraft landing on shipboard are plagued by hot exhaust plumes, very powerful shipboard radar that interferes with aircraft systems, inaccurate anemometers (wind measuring devices), and problems associated with high sea states such as strong, turbulent winds and extreme values of ship pitch, heave, and roll.

Figure 40. First US Navy shipboard helicopter landing: Sikorsky XR-4 aboard SS Bunker Hill, May 1943 (US Govt. image, courtesy of K. Long)

Wilkinson [135] gives an excellent summary of the demands a helicopter pilot landing on shipboard may face:

> "As the helicopter enters the ship air wake, the pilot is forced to compensate for disturbances, initially to the aircraft flight path, and finally to the position over the landing spot. Unexpected gusts may force the aircraft dangerously close to the flight deck and superstructure, or may move the helicopter away from the ship into a position where the pilot loses vital visual references. While the pilot is fighting to maintain accurate position, he has less spare capacity to consider his next move and the situation becomes unpredictable. In extreme wind conditions, the pilot may reach the limits of control authority with the result that there is insufficient manoeuvre power to compensate for the air wake disturbance." [135]

2.5.1 Navy “Dynamic Interface”

Because landing a helicopter on a moving ship deck is so inherently hazardous (Figure 41), the Navy has long operated a program to perform flight testing in this environment [136] with the stated goal of improving flight safety. This operation, known as the “Dynamic Interface” (DI) test program, has conducted over 180 at-sea shipboard rotorcraft flight test programs (Figure 42).

Figure 41. Helicopter accidents and incidents occur each year (US Govt. image, courtesy K. Long)

Figure 42. Helicopter landing on shipboard (photo by K. Long, US Govt. image, courtesy of K. Long)

For understanding the airwake over the ship, the Navy DI program uses techniques including shipboard flight tests, wind tunnel tests, computational fluid dynamics (CFD) models, and sampling the airflow vector velocities at various points in the flow field behind the superstructure in the helicopter landing zones with handheld anemometers. Sensors such as lidar detectors or particle image velocimetry (PIV) devices are continually being evaluated and incorporated into the program as improvements are made in the technology.

2.5.2 Operational Envelopes

During the many flight tests and analytic programs which the Navy Dynamic Interface program conducts each year, much valuable data about ship airwake is gathered and archived. Common problems and limitations are well known and yet the pilot does not receive most of this information. Navy flight test engineers have suggested that shipboard rotorcraft flight safety might be improved if the pilot could be presented with more detailed or dynamic information without being distracted [10] from the main task of landing the helicopter.

The current method of communicating the airflow information gathered by the Navy DI program to the pilots consists of publishing pre-computed operational envelopes (Figure 43)(Figure 44) listing allowable wind conditions for many ship-rotorcraft combinations [136]. The envelope conveys a go/no-go decision, essentially a binary output, and does not state which safety considerations motivate a given operational limit. Pilots check the published envelope for their helicopter before beginning any approach, and they only fly the approach if they are within the envelope. This procedure has the advantage of providing clear, simple direction to the pilots under all wind conditions. However, this means that if the winds shift out of the envelope during the approach, or some other event occurs that changes the airflow over the landing site, such as a helicopter on an upwind spot starting up its rotor, a hazardous condition can occur of which the pilot is unaware. This type of situation has been demonstrated to be a causal factor in many accidents and incidents [81].

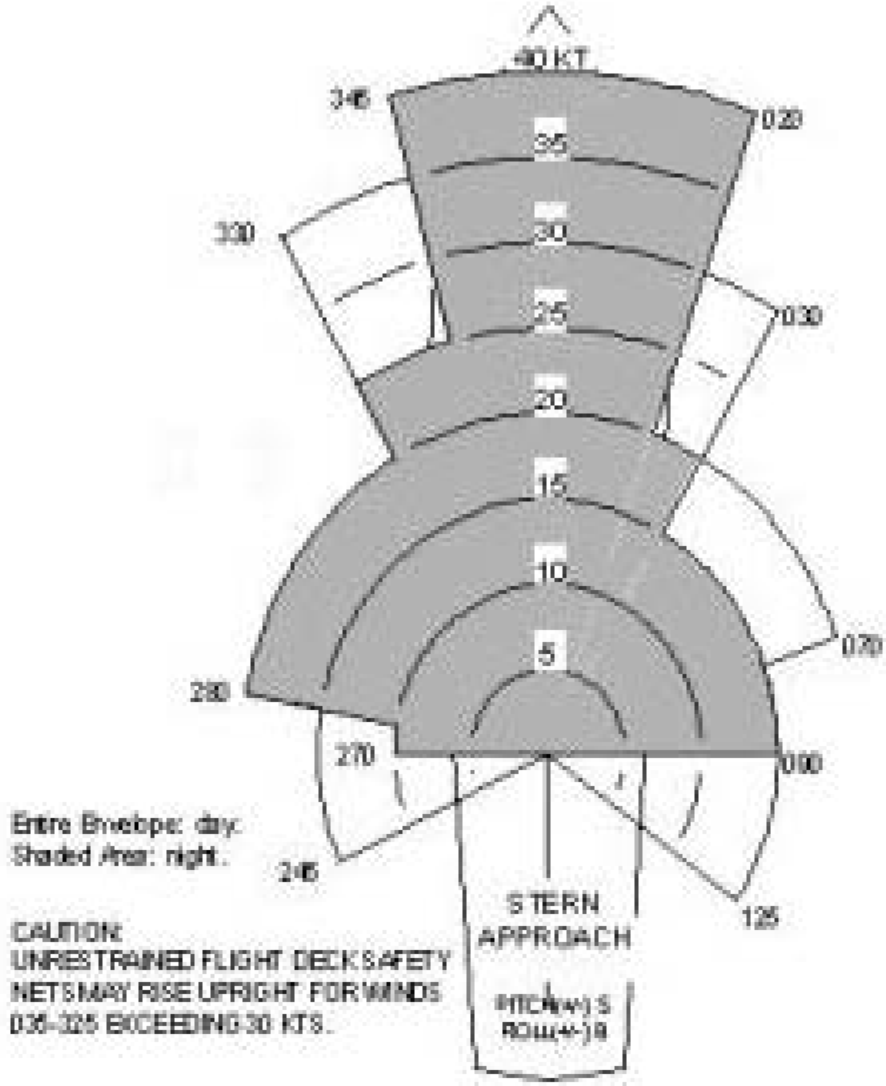


Figure 43. Shipboard rotorcraft operational envelope (US Govt. image, courtesy of K. Long)

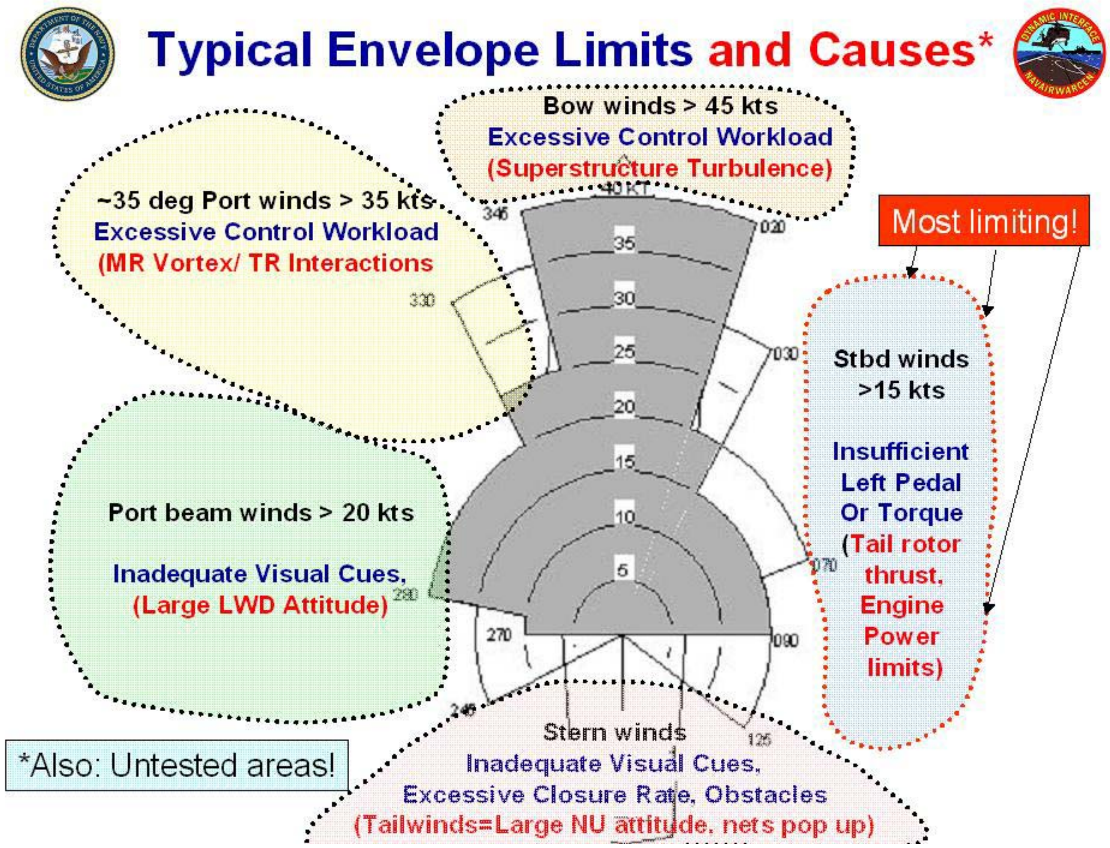


Figure 44. Navy shipboard rotorcraft testing yields extensive quantities of data and knowledge (US Govt. image, slide courtesy of Kurt Long)

In one recent incident, a helicopter tipped over while parked on a moored ship with the co-pilot at the controls. In an analysis of the incident, it was determined that the ship came loose from its moorings at one point, causing it to slowly drift into the wind, which led to a change in the wind direction over the deck. The helicopter was parked on the pitching and rolling deck, and as the wind over deck shifted and the deck continued pitching and rolling, the combination destabilized the helicopter, causing it to topple over [81]; fortunately, there was no loss of life. Navy flight test engineers have expressed the belief that a dynamic flight-deck visualization could have prevented incidents like this one [60].

2.5.3 Pilot Ratings of Landing Difficulty

In flight test programs, there is a requirement to quantitatively measure the difficulty level of all flight operations. As a result, several rating scales have been developed. We present descriptions of two of the major systems, the Cooper-Harper rating scale, and a modification and simplification used by the Navy's Dynamic Interface Flight Test Program, the Pilot Rating Scale (PRS).

2.5.3.1 Cooper-Harper Rating Scale

George Cooper, a test pilot employed by the Flight Operations Branch at Ames Research Center, developed the "Cooper Pilot Opinion Rating Scale" in 1957 as a result of the necessity to quantify pilots' judgments of aircraft handling in a manner that could be used in the aircraft stability and control design process [13]. It was subsequently modified in 1969 and became the Cooper-Harper Handling Qualities Rating Scale (Figure 45). This scale assigns a number from 1 (highly desirable) to 10 (major deficiencies) to each piloting task or required flight operation. It is still the standard way of measuring flying qualities used in flight tests today.

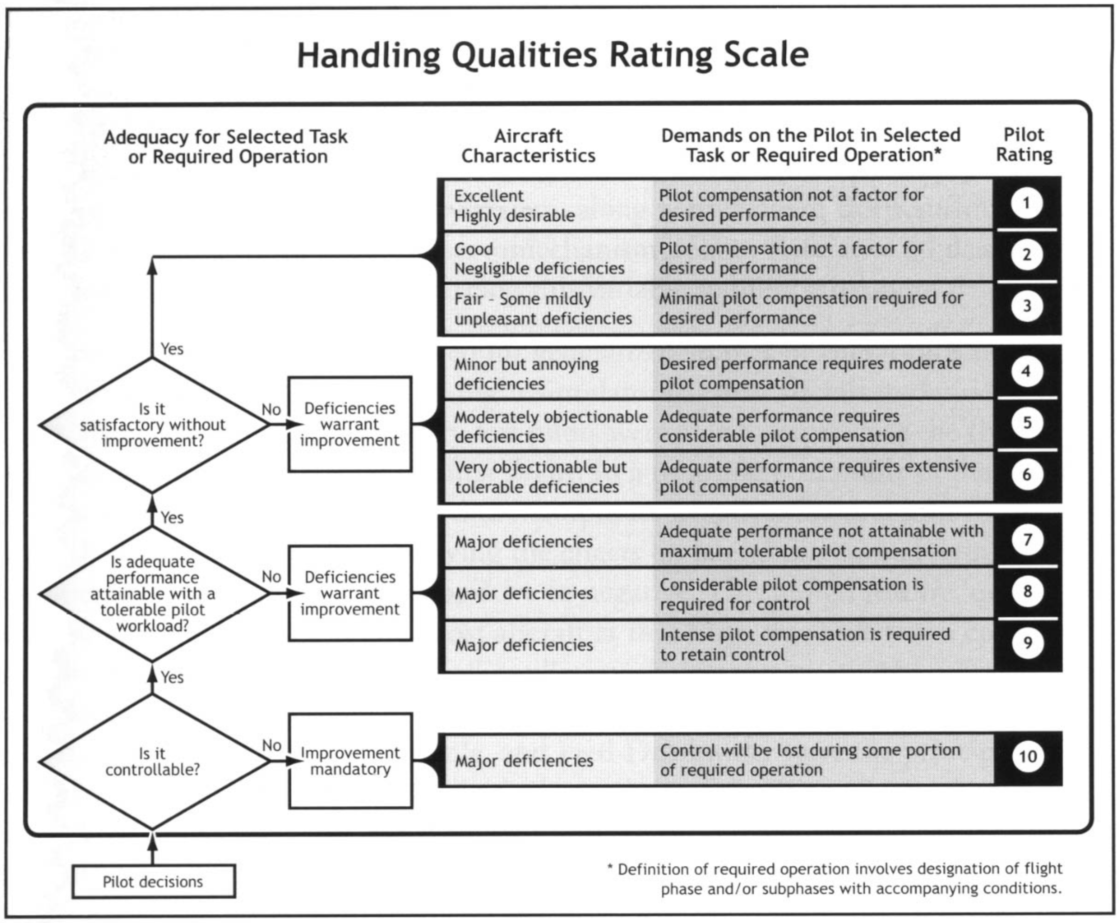


Figure 45. The Cooper-Harper Handling Qualities Rating Scale (US Govt. image, courtesy of K. Long)

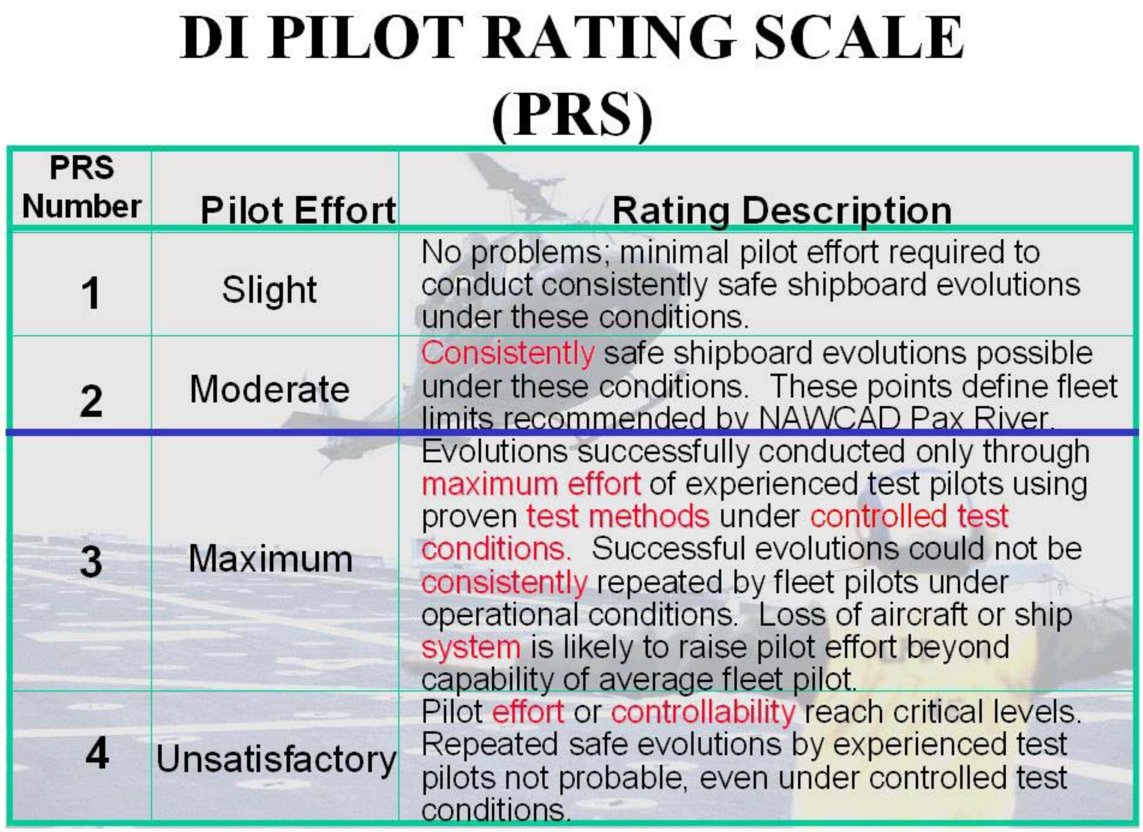
2.5.3.2 US Navy DI Pilot Rating System (PRS)

During US Navy Dynamic Interface (DI) flight test programs conducted before 1974, the pilots used the Cooper-Harper scale to assign ratings to each helicopter-shipboard operation [136]. However, the test pilots found that helicopter-shipboard operations were compound mission tasks that could not easily be broken down into smaller subtasks as required by the Cooper-Harper scale. A typical DI test sequence to be evaluated might include an approach, hover, descent, land, takeoff, and departure.

Additionally, because many of the DI tests occurred during breaks in real-world combat operations, the test pilots had to evaluate many different sets of test conditions in a very short time. Pilots in the DI flight test program determined that the Cooper-Harper scale was somewhat cumbersome for their specific use in helicopter-shipboard operations.

As a result, in 1974, they developed a simplified version of the Cooper-Harper scale with only four levels, called the Pilot Rating Scale (PRS) (Figure 46). This scale describes pilot effort on a range from 1 (slight) to 4 (unsatisfactory). The test pilot evaluates each operation and assigns it a number. If the rating is 1 or 2, that operation is deemed acceptable for Navy fleet operations. At 3 or 4, it is unacceptable. This scale is still in use today for Navy rotorcraft ship compatibility flight tests.

We used a version of the PRS to establish standardized levels of landing difficulty in the flight simulation usability study. More details on the procedure we followed are given in Chapter 4.



DI PILOT RATING SCALE (PRS)

PRS Number	Pilot Effort	Rating Description
1	Slight	No problems; minimal pilot effort required to conduct consistently safe shipboard evolutions under these conditions.
2	Moderate	Consistently safe shipboard evolutions possible under these conditions. These points define fleet limits recommended by NAWCAD Pax River.
3	Maximum	Evolutions successfully conducted only through maximum effort of experienced test pilots using proven test methods under controlled test conditions. Successful evolutions could not be consistently repeated by fleet pilots under operational conditions. Loss of aircraft or ship system is likely to raise pilot effort beyond capability of average fleet pilot.
4	Unsatisfactory	Pilot effort or controllability reach critical levels. Repeated safe evolutions by experienced test pilots not probable, even under controlled test conditions.

Figure 46. US Navy Dynamic Interface Pilot Rating Scale (PRS) (US Govt. image, slide courtesy of Kurt Long)

2.6 Summary

Although there has been a great deal of related work from disparate fields (including scientific visualization, human factors in aviation, aviation displays, and US Navy shipboard rotorcraft compatibility tests) surrounding this thesis project, the thesis itself breaks new ground by combining old fields in new ways, and presenting a new type of visualization. Applying HCI techniques to airflow hazard visualization in the cockpit had not yet been done before this research was undertaken.

Chapter 3 ■

Low Fidelity Prototype

3.1 Introduction

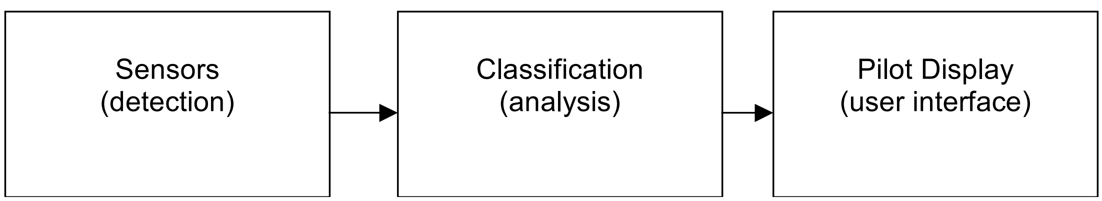
In this chapter, we discuss the initial stage of the user-centered design process we followed to develop the architecture of the visual hazard display system: the creation of a low-fidelity prototype. We performed a usability test with domain experts to validate the idea and to refine design choices for visual indicators. The results from the low-fidelity prototype usability study informed our design process. More details on the low-fidelity prototype usability study can be found in Aragon [4].

In Chapter 4, we will describe our implementation of the system in a high fidelity, aerodynamically accurate commercial flight simulator and the performance of a three-phase usability study. As it was an iterative process, we frequently found ourselves modifying and refining our design and assumptions with each set of new inputs from different users. We believe this contributed to the success of the final system, both in terms of pilot acceptance of the system and pilot performance.

3.2 Hazard detection architecture

A complete onboard airflow hazard detection system would consist of three major components: sensors; classification and analysis; and display (human interface). Our research addresses the display stage, but we describe the others here to illustrate the problem in context (Table 1).

Table 1. Simplified representation of airflow hazard detection system



3.2.1 Sensors/detection

Recent technological advances in sensor technology, especially Doppler lidar (Figure 47)[80], PIV (Particle Image Velocimetry) [85], and forward-looking microwave or infrared radar [15], offer the potential for aircraft-based sensors which can gather large amounts of airflow data in real time. There are currently available commercial systems utilizing this technology to detect moderate-scale airflow disturbances such as microbursts and windshear [21, 138]. Current research into airflow detection techniques such as lidar is promising; it is believed that within a few years hardware capable of being mounted on an aircraft will be able to reliably scan the area a few hundred feet ahead of the aircraft and sample air particle vector velocities at one-foot intervals or less [60].

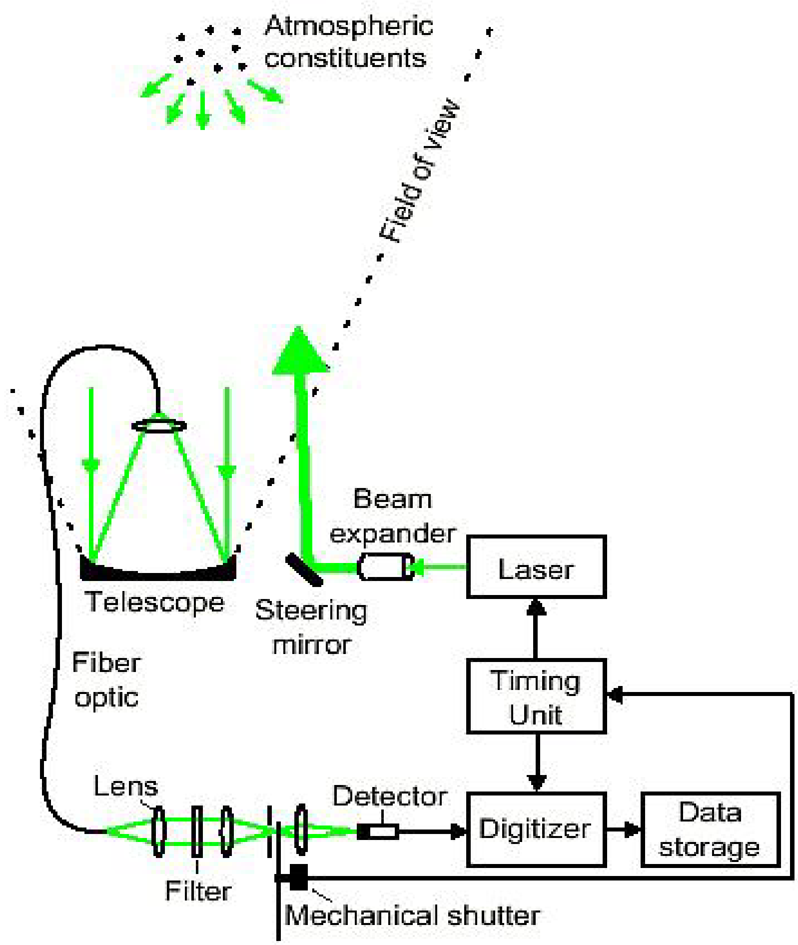


Figure 47. Lidar schematic (reprinted with permission by T. Duck, http://aolab.phys.dal.ca/pages/LidarBasics)

Helicopter-mounted lidar devices are currently being flight-tested at the Japan Aerospace Exploration Agency (Figure 48) [6, 37]. With the development of such devices, onboard detection systems that can convey detailed, specific information about airflow hazards to pilots in real time become a possibility.

Figure 48. A helicopter-mounted lidar system undergoing test flights at the Japan Aerospace Exploration Agency (photo courtesy of Naoki Matayoshi)

3.2.2 Classification/analysis

This area concerns the development of algorithms to input the particle positions and vector velocities, other variables such as density altitude, aircraft gross weight, and power available; to compute the locations of the areas of flow which may produce a hazard to this particular aircraft on this particular day; and to output the three-dimensional coordinates of the hazard location in real time. Techniques such as the identification of swirling flow [50, 92, 106] can be used to detect vorticity (Figure 49).

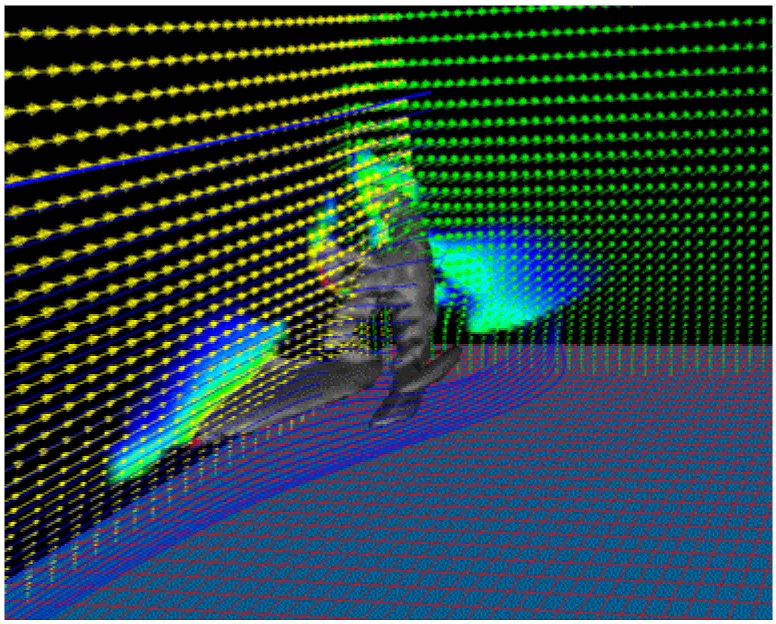


Figure 49. Developing turbulent or swirling flow (reprinted with permission by D. Thompson, http://www.erc.msstate.edu/~dst/research_new/feature_mining/detection/swirling_gallery.shtml)

3.2.3 Display to the pilot (user interface)

Given the airflow data and the known hazard areas, the problem then becomes to organize this vast amount of data, describing millions of particles swirling in different directions, and present it to the pilot in a manner that does not interfere with the primary task of operating the aircraft safely. An interface is required that can present potentially large amounts of data to the pilot in a non-intrusive yet comprehensive manner in real time.

3.3 Motivation for visual interface usability study

Since an airflow hazard detection system generates an enormous amount of disparate data that must be organized and presented to a human operating a complex machine in a high-workload environment, an efficient method of human-machine communication is required. The human visual system has the highest bandwidth of all the senses. It can process gigabytes of data in real time and organize it into patterns that the brain can use to draw conclusions and act very quickly. It therefore makes sense to organize the airflow data into some type of visual display.

As with any type of user interface, usability evaluation is important to ensure that the display most efficiently supports the human operator's performance. Given the demanding environment and the relatively small population of highly trained pilots, it is especially critical to conduct a usability study before designing an airflow hazard display system.

During potentially hazardous conditions, high winds, low visibility, or extreme ship motion, the pilot’s attention is naturally focused outside during the critical landing moments; he or she does not want to look down at a cockpit instrument display. In designing our experiment, we assumed pilots would prefer an augmented-reality hazard visualization display (as was verified during the usability study). However, the head-up display must be carefully designed not to distract from the key shipboard visual cues, which may be degraded during a challenging nighttime or poor-weather landing on a ship. Studies have shown that head-up displays with superimposed symbology may on occasion cause performance problems due to attentional capture by the perceptual grouping of the superimposed symbols [66, 67]. "Scene-linked" head-up displays, or displays where there is no differential motion between the superimposed symbology and the outside scene, avoid this type of distraction. For this reason, we decided to develop a head-up display where the hazard indicator is three-dimensional and appears to be physically part of the world.

As the first step in our user-centered design process, we constructed a low-fidelity horizontal prototype (a relatively full-featured simulation of the interface with no underlying functionality) [82] of an augmented-reality hazard visualization system that included many different types of hazard indicators. The usability study on the low-fidelity prototype had two main goals: first, to determine whether presenting airflow hazard data to helicopter pilots would be helpful to them; and second, to obtain expert feedback on the presentation of sample hazard indicators, from which we could refine our design choices.

We decided to perform interactive prototyping [82], a technique where the prototype is altered on the fly as the test user comments on its effectiveness. This enabled us to rapidly modify the design and obtain feedback on multiple variations in a single session.

3.4 Selection of Platform for Low-Fidelity Prototype

The next task was to identify the best tool for creating a relatively realistic, three-dimensional visual simulation of the helicopter pilot's view out the cockpit windscreen during the final approach to a shipboard landing. The tool was required to support rapid prototyping, 3D modeling, and simple animation. It was especially important that we be able to create new hazard visualizations within minutes, as we were hoping to get feedback from the study participants and implement their suggestions during the session so as to tighten the feedback loop.

Consultation with Navy flight test engineers provided detailed descriptions of what a landing approach should look like. Additionally, we were provided with an extremely detailed 3D CAD model of a Spruance-class destroyer (DD 963) (Figure 50)(Figure 51). An ideal prototype platform would be able to use this data to render a realistic approach.

Figure 50. USS Spruance DD 963 (US Govt. image, courtesy of K. Long)

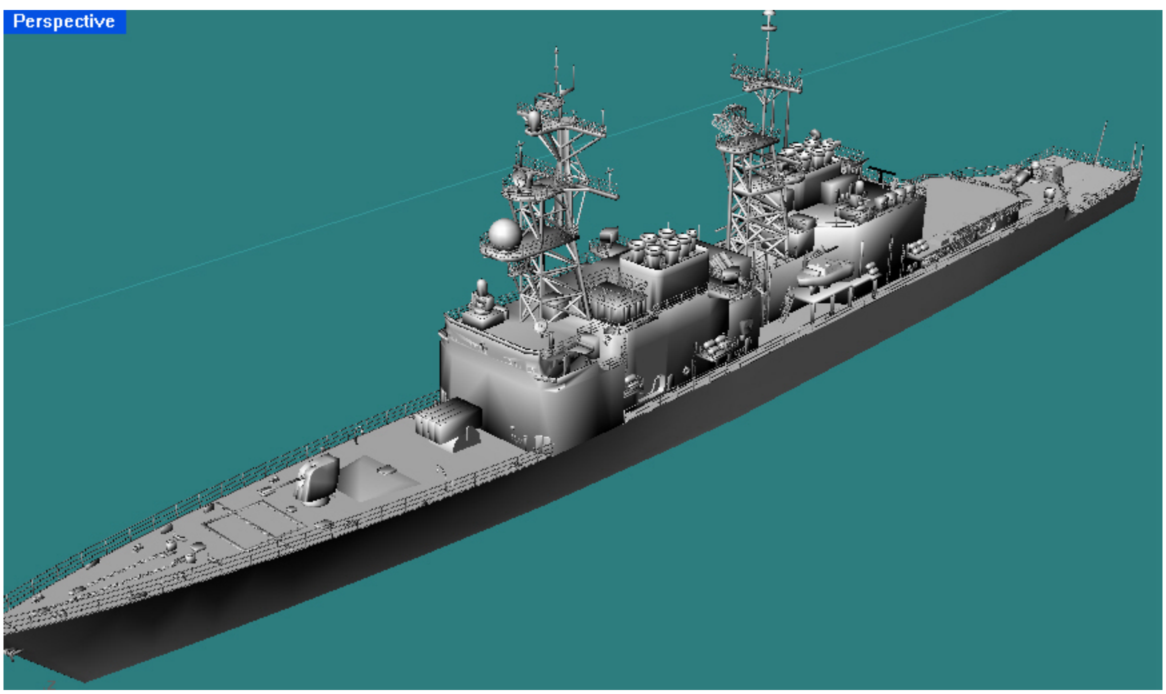


Figure 51. Rhino3D model of DD 963

Three approaches were considered for the prototype software platform: a low cost, off-the-shelf flight simulator; a 3D animation system; and a 3D CAD tool.

The Microsoft Flight Simulator [70] was considered because it offered the possibility of the pilots being able to use a joystick (thus rendering the simulation relatively more realistic than some of the other platforms) and potentially the opportunity to alter the visual hazard display without affecting the flight simulation. However, there was no convenient interface for importing the existing ship model into MS Flight Simulator. Additionally, it was clear that modification of the prototype could not be done on the fly, but would require a non-trivial amount of programming time.

We also investigated various 3D animation systems such as WildTangent [134], VRML [41, 127], and Flash [63]. However, although these systems could handle the animation well, the overhead for changing hazard indicators was considerable, essentially comparable to working in a programming language. (Actual programming languages, such as Java, were ruled out for the same reason.)

The CAD modeling tool we selected, Rhino3D [93], offered rapid construction and alteration of the prototype scenarios and easy access to the ship model data. It was very easy and quick to create many different types of hazard indicators and modify their shape, location, color, texture, and transparency. Although not a flight simulator, the CAD program allowed us to simulate the final approach to landing by rotating and zooming the model of the ship with the hazard indicator displayed above it.

The choice of which types of hazard indicators to display was initially made after a literature search of aviation displays, including head-up display (HUD) symbology, synthetic vision systems, and augmented and virtual reality symbology used in aircraft.

We attempted to display as wide a selection as possible, and to show images that we surmised might be unsuitable as well as those we thought would be helpful. We also allowed for modifications during the study, and left time for the pilots to make suggestions, which we would then implement during the interviews.

3.5 Methodology

We recruited three highly experienced (>1700 hours) helicopter pilots and flight test engineers, all with shipboard landing experience. Each session with a participant pilot consisted of a 1 ½-hour interview with the pilot in front of a projection screen. All sessions were videotaped. Two experimenters conducted the session, one operating the computer and the other interviewing the pilot and taking notes.

The operator-experimenter used the Rhino3D CAD program to display on the projection screen a model of the ship (DD 963), with a hazard indicator displayed on the ship's deck where hazardous airwake might be found. The operator manually simulated a helicopter's view of an approach to landing on shipboard as the pilot watched and commented. A wide selection of different types of hazard indicators were stored in layers in Rhino3D, so that features could be selectively turned on and off by the operator. The features that were varied in the hazard indicator included shape, location, color, texture, transparency, depth cueing, and motion.

The following set of figures (Figure 52)(Figure 53)(Figure 54)(Figure 55)(Figure 56)(Figure 57) depict a series of frames from the videotape taken from one such simulation. The video camera was set up to focus on the projection screen so that the pilot was not visible on the film.

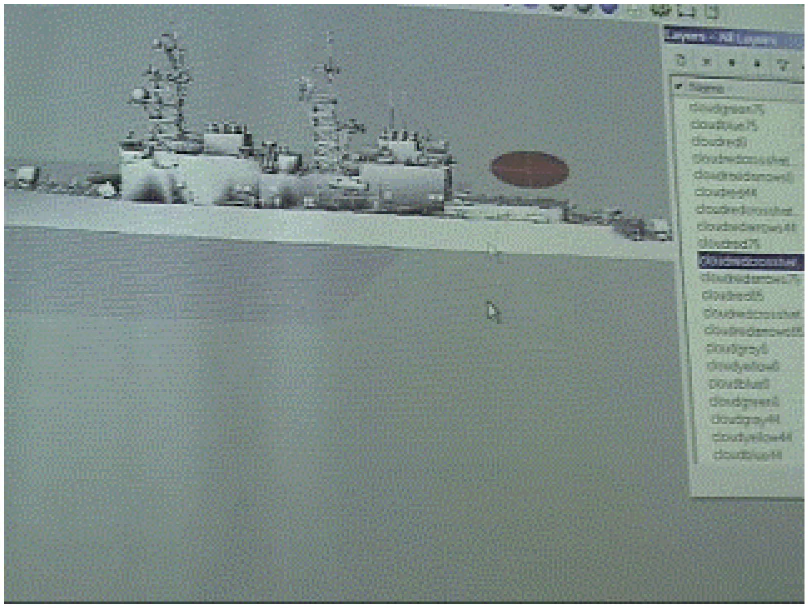


Figure 52. As simulated in Rhino3D, this is the beginning of the helicopter's approach to DD963; 180 degrees off and abeam the landing spot

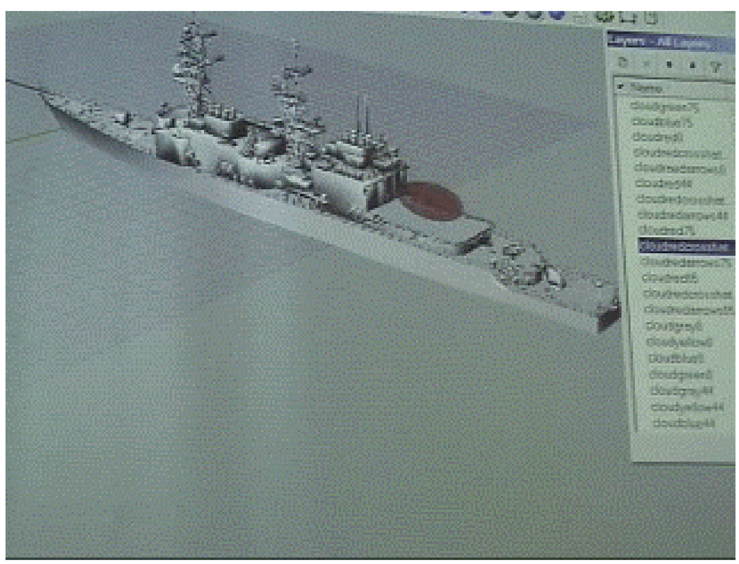


Figure 53. The helicopter continues the approach toward the ship. A sample hazard indicator is visible over the landing spot.

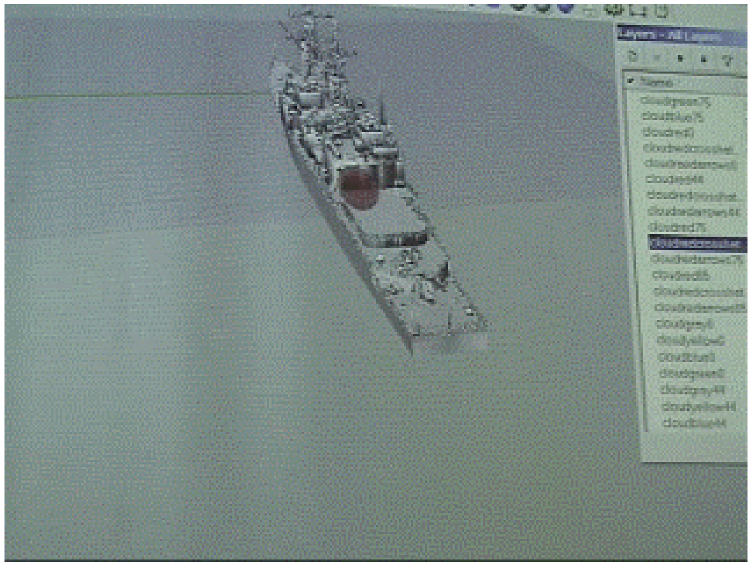


Figure 54. Helicopter turns onto final approach. To the right of the image is a menu of layers in Rhino3D; various hazard indicators can be turned on and off with a click.

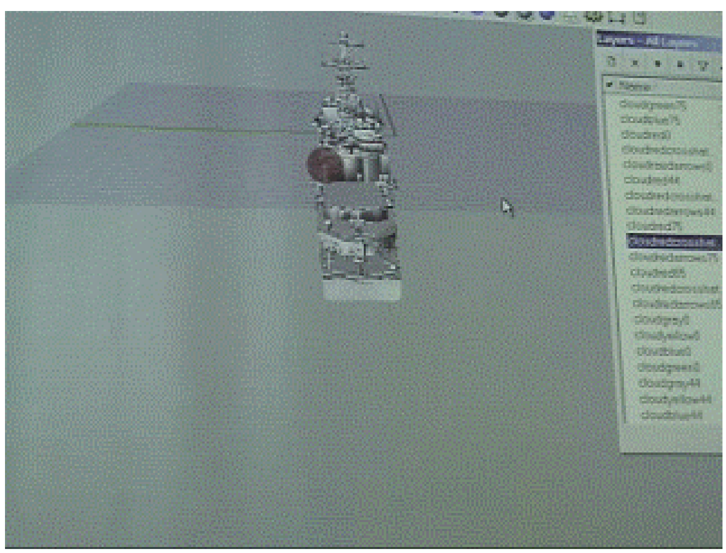


Figure 55. Helicopter established on final approach

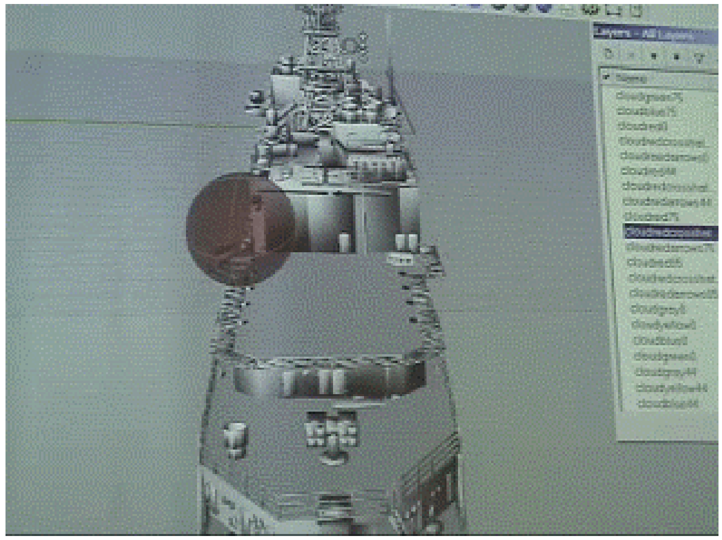


Figure 56. Helicopter is on short final, approaching landing spot on ship deck aft of hangar superstructure. DD963 only has one landing spot.

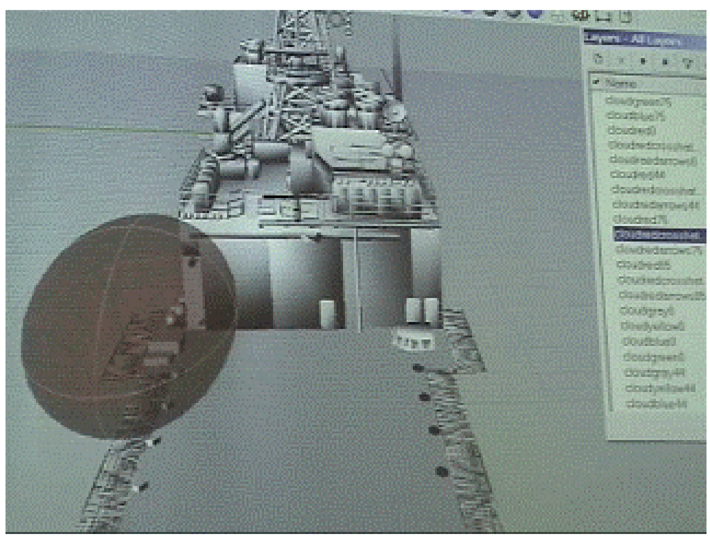


Figure 57. Helicopter is about to land aft of ship hangar. Hazard indicator can be clearly seen. Pilot can make comments on shape, color, transparency, etc. and have indicator modified as he speaks.

Feedback was solicited from the pilots as they watched the simulations. If the pilot suggested a change, the operator implemented it on the fly and the pilot was asked to judge whether the change was an improvement. The experimenter asked both specific and open-ended questions throughout the interview designed to elicit the pilots' expertise.

Using the pilots' responses, we attempted to assess the efficacy of presenting airflow data in flight, and to select the most efficacious (as judged by the pilots) visual presentation for the hazard indicator.

3.6 Participants

In choosing participants, we sought pilots with a great deal of helicopter experience and, ideally, experience with shipboard landings of large military helicopters. Finding pilots with the requisite domain-specific knowledge was challenging. The final test group for the prototype consisted of two military pilots and one experienced civilian helicopter pilot:

All pilots were male, had normal or corrected-to-normal vision, were not color-blind, and were right-handed. Pilots were not compensated for their time.

Participant 1: Navy helicopter test pilot, 2,000 hours of flight time, 17 years experience.

Participant 2: Navy helicopter flight test engineer, 4,000 hours of helicopter simulator time, 100 hours of flight time, 17 years experience with shipboard helicopter flight tests.

Participant 3: Civilian helicopter flight instructor, 1740 hours of flight time, 3 years experience.

3.7 Results

Results of the usability study on the rapid prototype were encouraging, but in some respects surprising as to the types of display features pilots found helpful. All participants said they liked the system and would use it if it were installed on their aircraft. As they viewed the interface, the pilots repeatedly stated that they wanted such a hazard visualization tool.

As to the type of visualization, the strongest overriding principle that emerged from this experiment is that helicopter pilots are using all their attention to focus on the extremely demanding task of landing on a moving ship deck, perhaps under low visibility conditions or at night, and the hazard indicator must not distract from that focus. To that end, the participants favored much simpler imagery than we would have expected.

The pilots strongly rejected the use of flow visualization indicators, and especially of motion to indicate flow. Given the manner in which fixed-wing pilots look for natural flow indicators such as dust devils near the runway, smoke plumes, wind-blown vegetation etc., we had anticipated that helicopter pilots would prefer a dynamic flow visualization, capable of indicating the direction and velocity of particles in the hazardous region. However, the participants exhibited resistance to such a design. All participants, even while reiterating their desire for 3D hazard visualization, stated that motion was distracting during the approach and particularly during the critical moments near touchdown. A static visualization, even supplying less information, was strongly preferred over a dynamic hazard indicator. That is, the participants sought a real-time decision support tool, not an airflow analysis tool.

This study also highlighted a strong preference on the part of the pilots for a hazard visualization system in which the hazard indicator appears in the physical scene. The pilots confirmed that their attention was focused outside the cockpit during the critical landing moments, and that they did not want to look down at a cockpit instrument display, especially during potentially hazardous conditions. The pilots strongly preferred an augmented-reality hazard visualization display on a head-up display. However, the display must be carefully designed not to distract from the key shipboard visual cues, especially when these are degraded during a challenging nighttime or poor-weather landing.

Below we describe the hazard display parameters that were varied in the prototype usability test, and the results obtained for each.

3.7.1 Color

We showed hazard indicators in single and in multiple hues, using colors spanning the spectrum (Figure 58)(Figure 59)(Figure 60). All pilots preferred single-color hazard indicators, and indeed, preferred only two colors for the final system: yellow for caution and red for danger. Yellow, according to the participants, should indicate an airflow hazard that could necessitate strong pilot input to stay safe, but where the aircraft should maintain controllability. Red should indicate danger, an airflow hazard that would likely be beyond the limits of the aircraft and would put its controllability in question.

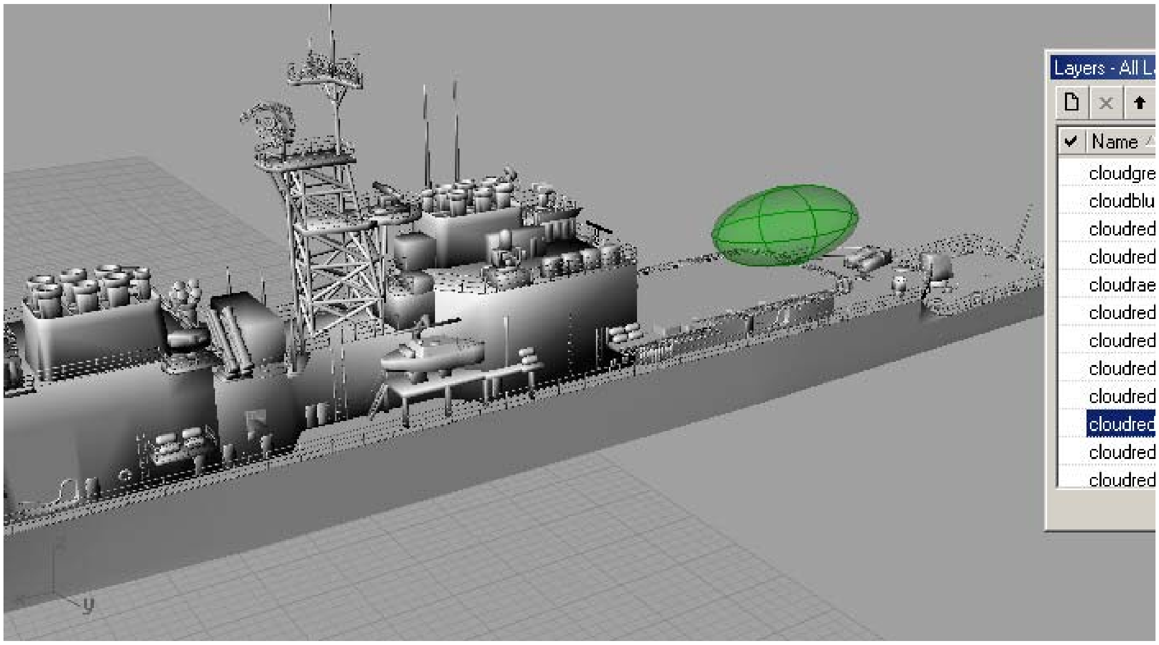


Figure 58. Color choice for hazard indicator: green

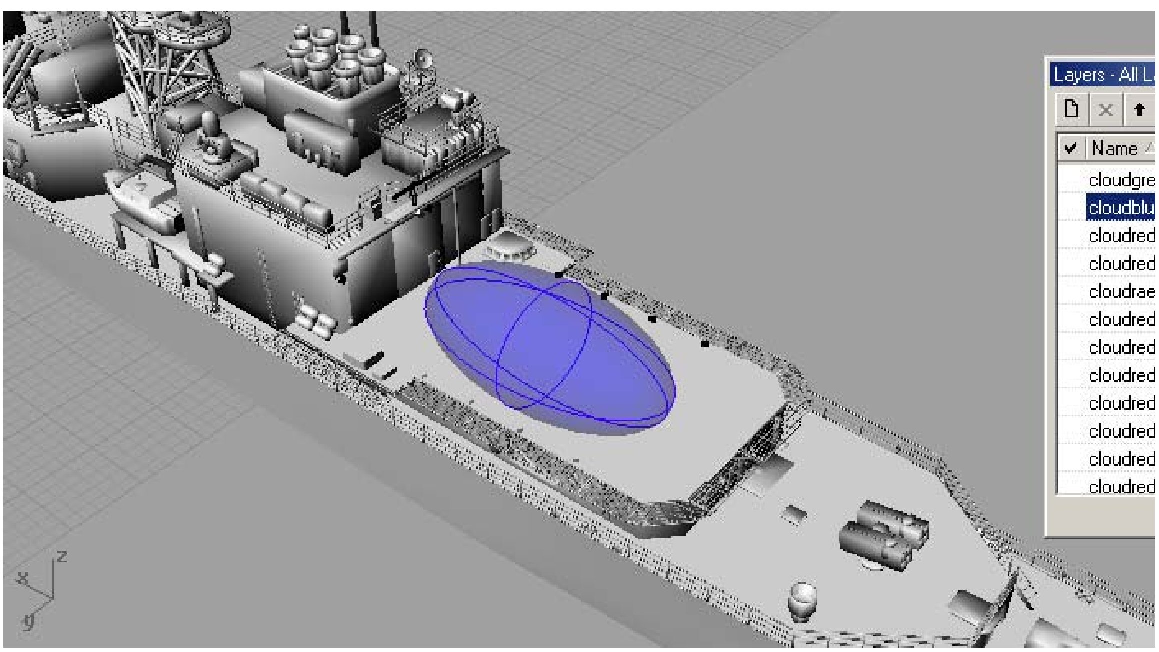


Figure 59. Color choice for hazard indicator: blue

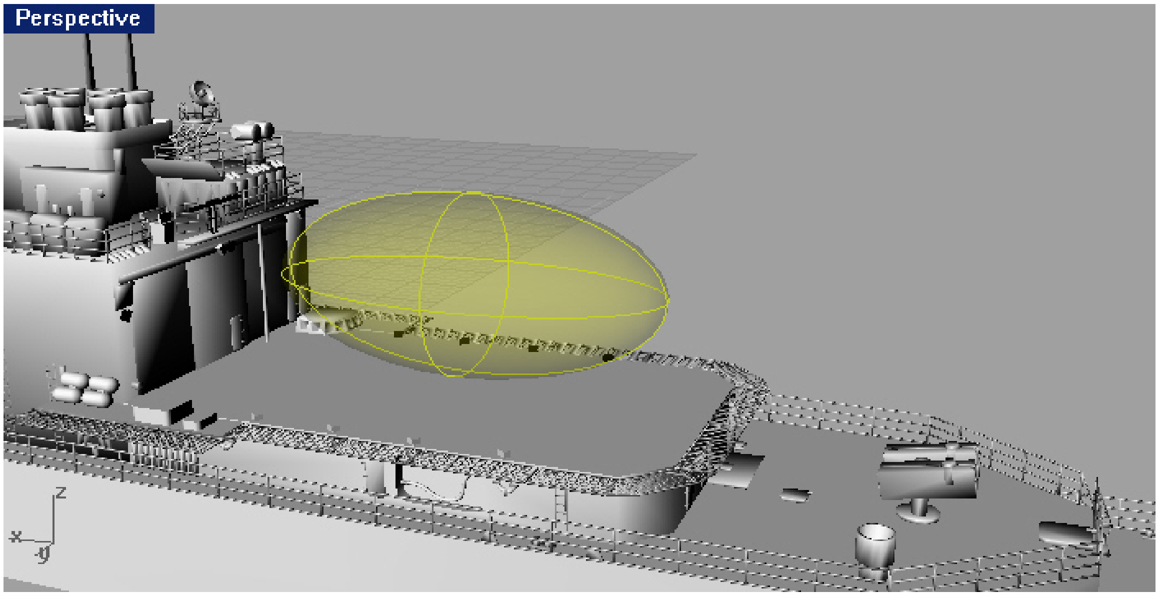


Figure 60. Color choice for hazard indicator: yellow

We were surprised to find the pilots unanimous on the point that a hazard indicator should be rendered in a single color (either red or yellow). Multiple-color hazard indicators were considered distracting and confusing. When the experimenters pointed out that a vortex core could have very strong winds but the outer portion of the vortex might not be as hazardous, so that a two-color indicator with a red core and a yellow mantle might be useful, the pilots all disagreed, saying the red vortex core would be difficult to see or to locate correctly in a three-dimensional object. In addition to the overall view that the display would be confusing, a concern was also expressed that a two-color indicator could tempt a pilot to venture into the yellow mantle while attempting to skirt the red core. That is, the two-color indicator was thought to potentially support an incorrect decision to land in dangerous conditions.

3.7.2 Transparency

While holding other variables constant, we varied the transparency of the displayed hazard indicator from 20% to 80% (according to the Rhino software controls). This test was repeated for a range of objects. The pilots preferred an average transparency near 70%. While desiring a hazard indicator sufficiently opaque to come to the pilot's attention, participants noted the critical need for the pilot to be able to see visual cues on the ship behind the hazard indicator.

3.7.3 Depth Cues

We displayed hazard indicators that hovered above the deck and cast no shadow, and others that had a colored shadow projected onto the deck directly below the indicator. Of those with shadows, some had a connecting vertical line from the indicator to the deck shadow. All of the pilots preferred shadows below objects, stating that they helped the pilot to localize the 3D indicator in space. Pilot #1 said shadows alone might be sufficient for a shipboard hazard warning system: "just paint the deck red if I need to wave off." Pilot #2 liked the idea of a connecting line between the hazard indicator and the deck. No participant wanted tick marks or numeric information floating with the hazard indicators. Again, they preferred to keep it simple; the purpose is to let the pilot see the location and approximate severity of a hazard, not to help them measure or analyze it.

3.7.4 Texture

Recent studies have shown that applying various textures to a three-dimensional object can greatly increase user ability to understand the contours of that object [47]. In order to determine if these findings hold true for pilots landing on shipboard, we displayed hazard indicators having a series of arrows textured onto their partially transparent surface, to indicate the direction of airflow in that hazardous area, and asked pilots to compare them to indicators without the texture. Pilots #1 and #2 did not want the extra detail, saying it could be confusing or distracting. Even if the texturing gave them additional information about the airflow hazard, the pilots expressed concern that their limited spare attention could be overloaded. Pilot #3, the civilian pilot, was the only one that did not reject texturing the surface of the hazard indicator out of hand. He suggested striping as a possible symbology, reminiscent of the yellow and black caution tape that is a common symbol to most Americans.

3.7.5 Shape

We asked the pilots to comment on the effect of varying the shape of the hazard indicator, such as rectilinear transparent boxes, cloud shapes with rounded corners, spirals, rings both round and rectangular (Figure 61)(Figure 62)(Figure 63)(Figure 64)(Figure 65). The rectilinear and cloud shapes were favored over all others. Again, a preference for simplicity was displayed.

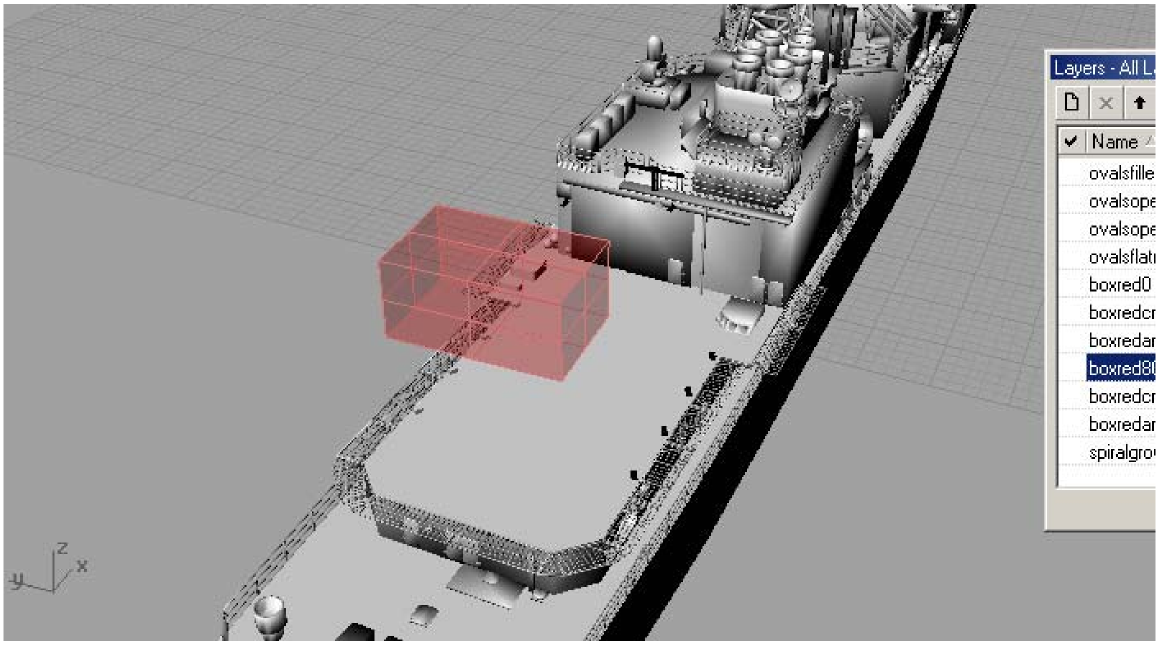


Figure 61. Hazard indicator shape: rectilinear

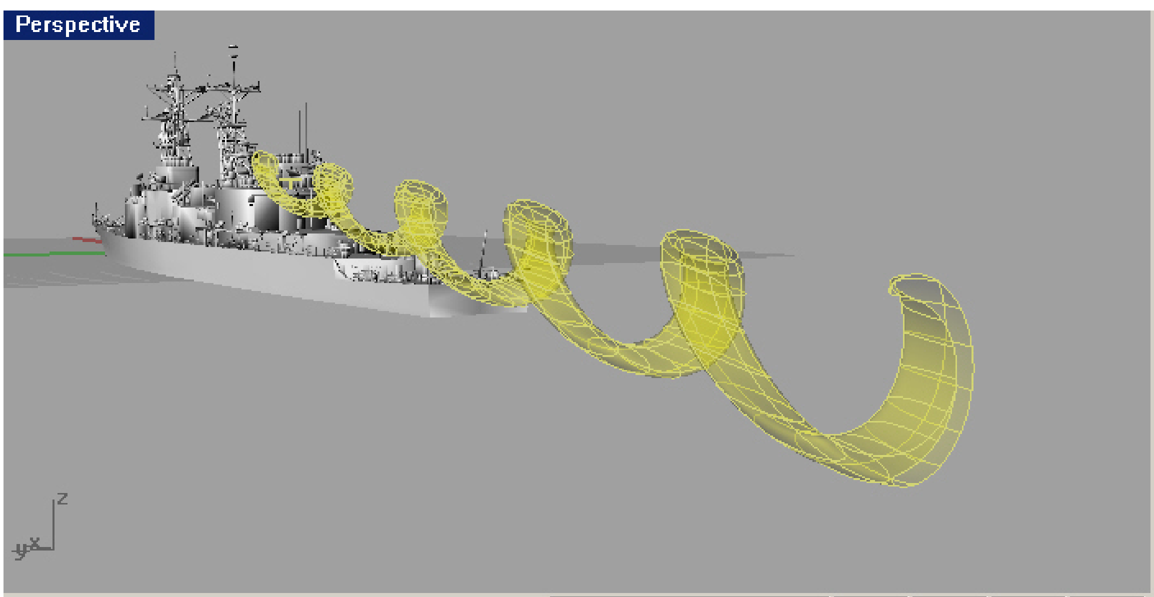


Figure 62. Hazard indicator shape: open spiral

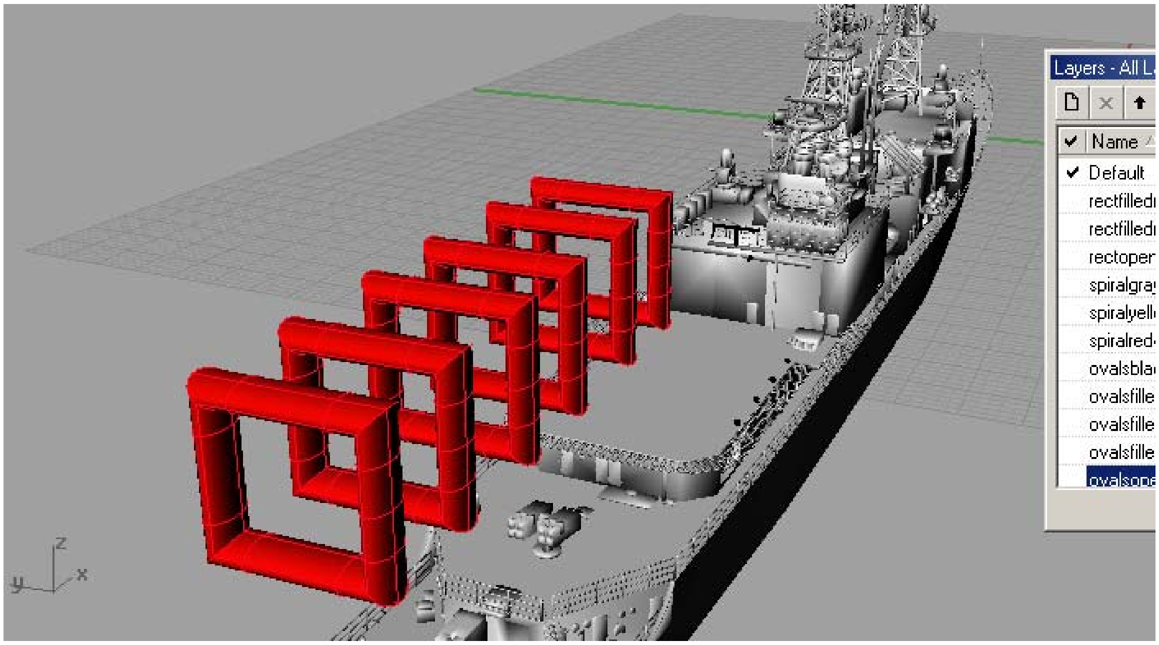


Figure 63. Hazard indicator shape: open rectangles

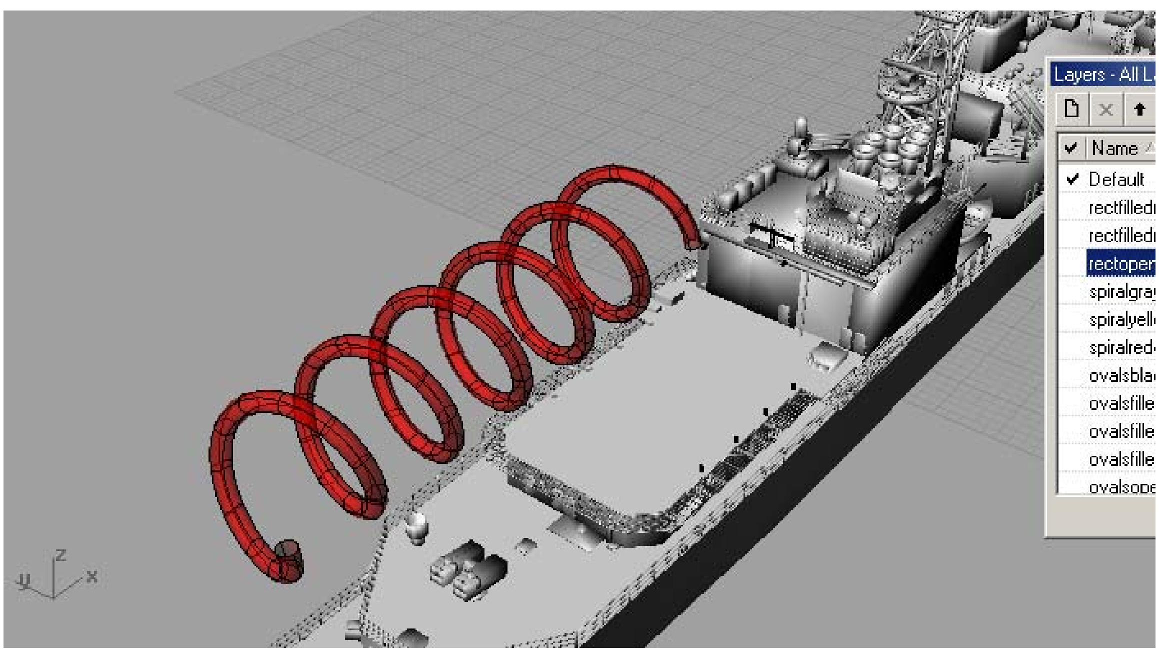


Figure 64. Hazard indicator shape: spiral

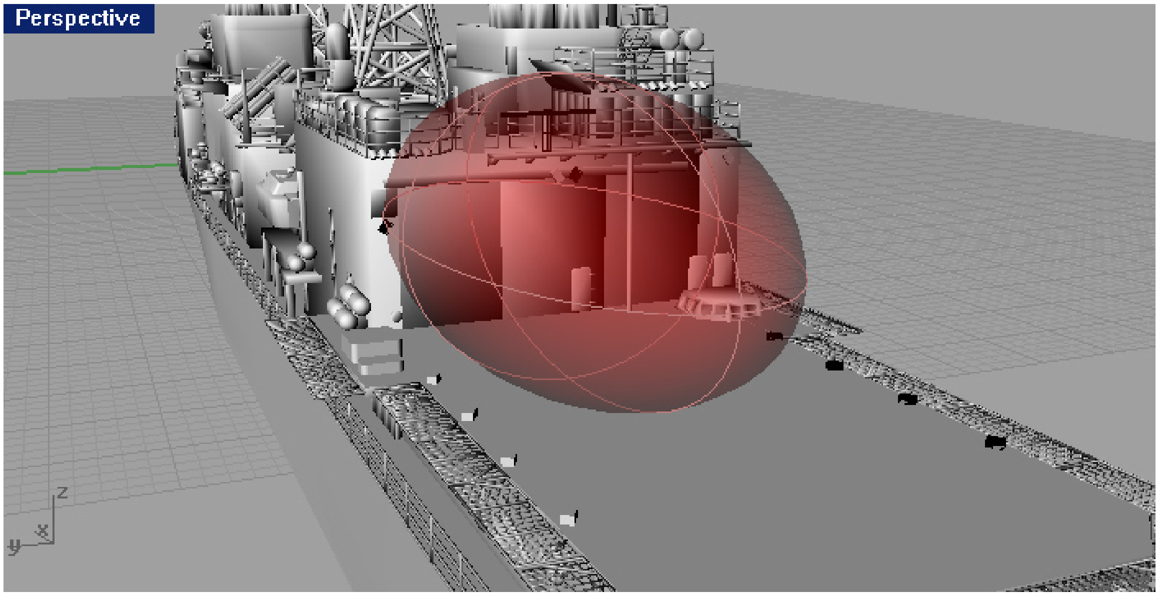


Figure 65. Hazard indicator shape: cloud

Pilots emphasized the importance of using standard symbology at all times. They warned of the danger a moment of confusion could cause, and strongly recommended that the symbology used in our head-up display conform to current aviation conventions; it was especially important that our symbols not have any chance of being confounded with other types of HUD symbology already in use.

One of the types of symbols we evaluated, and ended up rejecting due to pilot feedback, was a series of yellow rings (Figure 66)(Figure 67). The pilots felt that the yellow rings looked very similar to the "highway-in-the-sky" tunnel symbology that was used for navigation on some HUDs. That symbology was designed as a navigation aid where the pilot would fly through a series of rectangular outlines appearing to float in the sky, giving the appearance of a "tunnel." Our "yellow-rings" symbology was rejected based on this potential confusion; even a moment of pilot hesitation could be disastrous in real-world conditions.

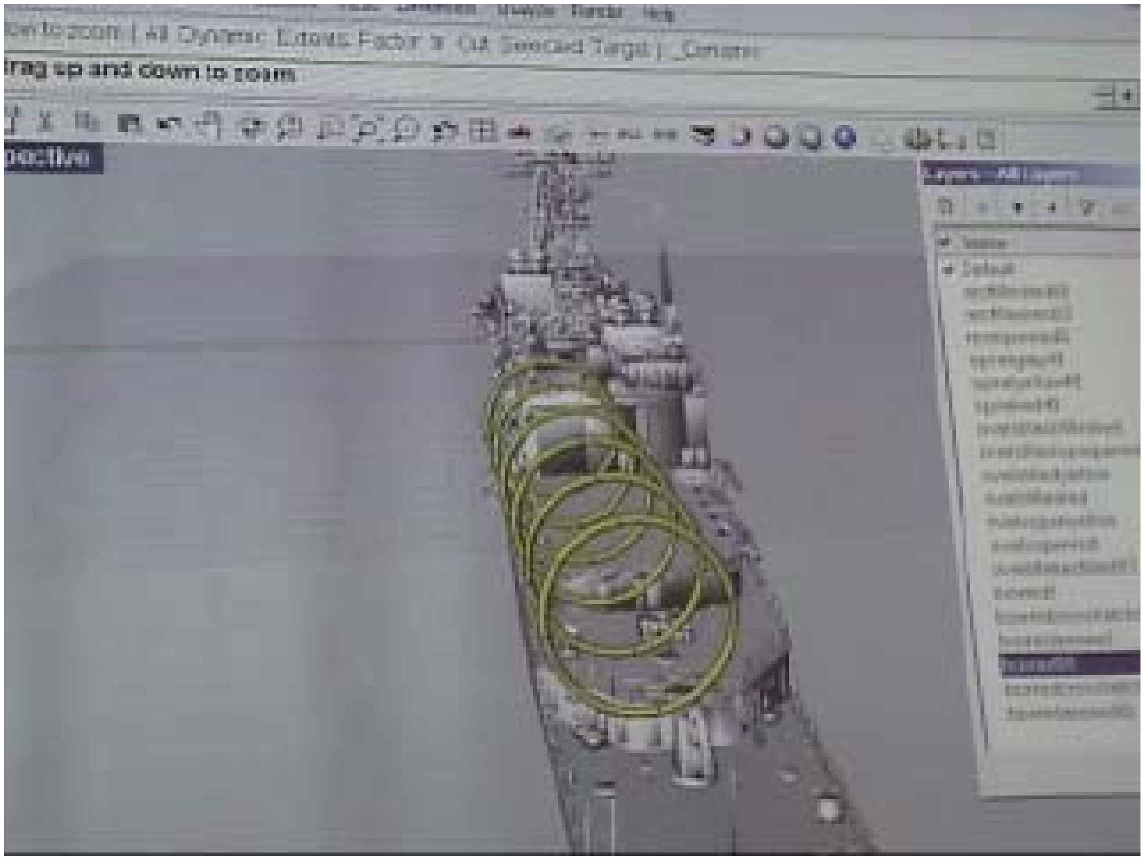


Figure 66. An example of unsuccessful imagery in the low-fidelity prototype -- a series of yellow rings to represent hazardous airflow

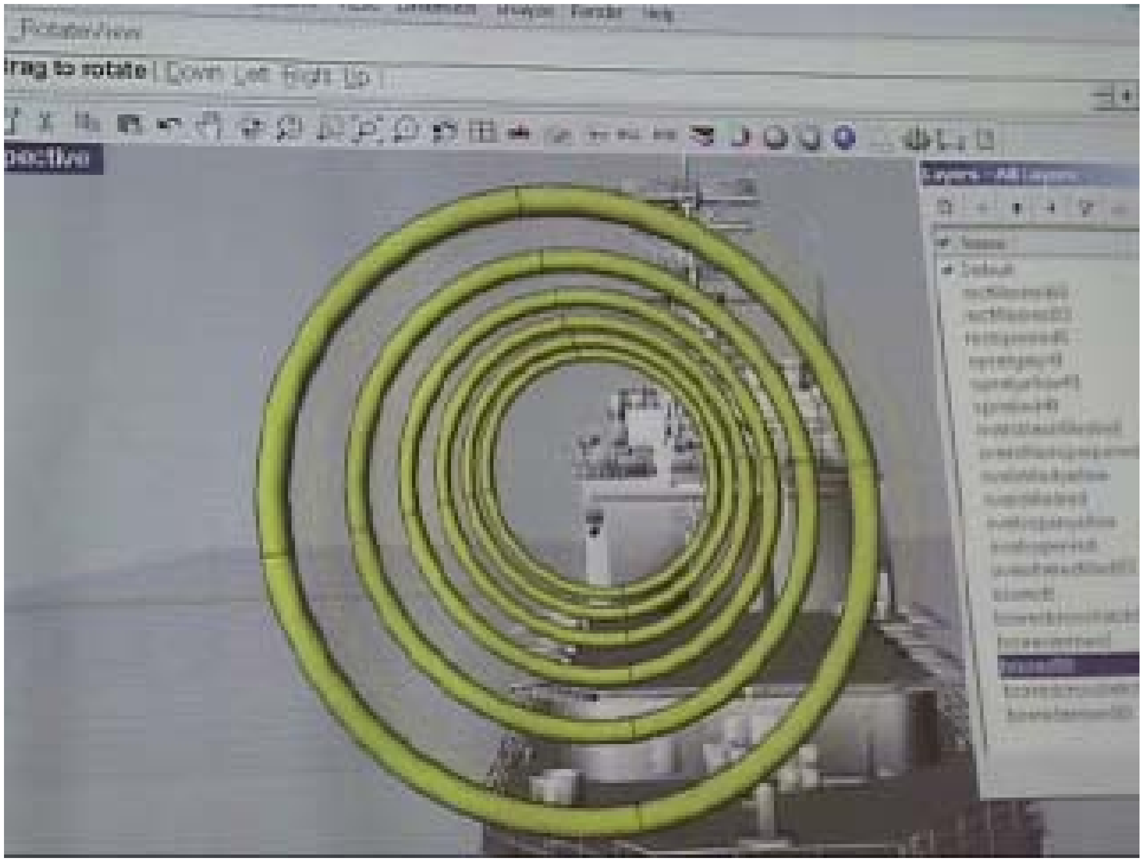


Figure 67. The ring symbology appears similar to the "highway-in-the-sky" tunnel symbology used on HUDs, and therefore may confuse the pilot or entice them to enter the "tunnel"

Although not completely standardized, current HUD symbology includes items like airspeed and altitude tapes, aircraft reference symbol, flight director, and roll scale pointer (Figure 68). The results from this low-fidelity prototype study helped us to select a design that was significantly different from any type of HUD symbology.

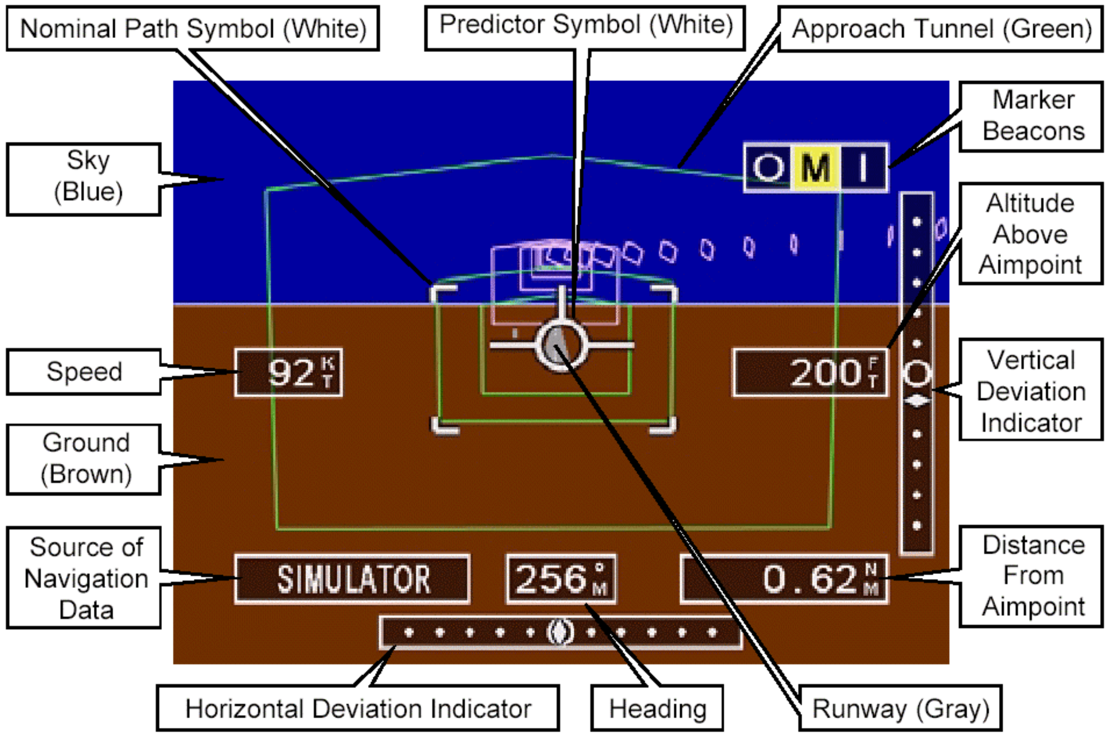


Figure 68. Example of tunnel-in-the-sky or highway-in-the-sky symbology (US Govt. image, courtesy of W. Holforty)

3.7.6 Motion (Animation)

We manually animated some of the hazard indicators, showed the pilots animated visualizations (Figure 69), and asked the pilots their opinion on the use of motion or animation in the hazard display. Although the pilots acknowledged that the turbulent airflow of concern to them was always in motion, there was a strong consensus that motion in the display, particularly fast motion, was distracting. Pilot #1 (the participant with the most experience landing on shipboard in actual hazardous conditions) said the visual indicators should absolutely not use motion at all. It was distracting, and in the worst case could induce vertigo, especially at night or in low-visibility situations. The pilot stated that if the indicators had to change their position in real time to indicate a change in the location of the hazard, they should move smoothly, and attention should be paid to the edges to make sure no flashing or other video artifacts appear that might distract the pilot from the task of landing. This pilot also stated that the indicators should fade in and out gradually in response to changing hazard conditions (unless the pilot turned them on or off.) A sudden appearance of a hazard indicator, where there had been none, could be startling and potentially dangerous. Likewise any rapid motion or disappearance out of the corner of the pilot's eye during the landing could be distracting and potentially dangerous. Pilot #2 concurred that there should be no motion in the hazard indicators. Pilot #3, the civilian pilot, stated that slow motion on the surface of the indicator could conceivably be helpful to give an indication of which way the airflow was moving within, but that in general, fast motion could be distracting and dangerous.

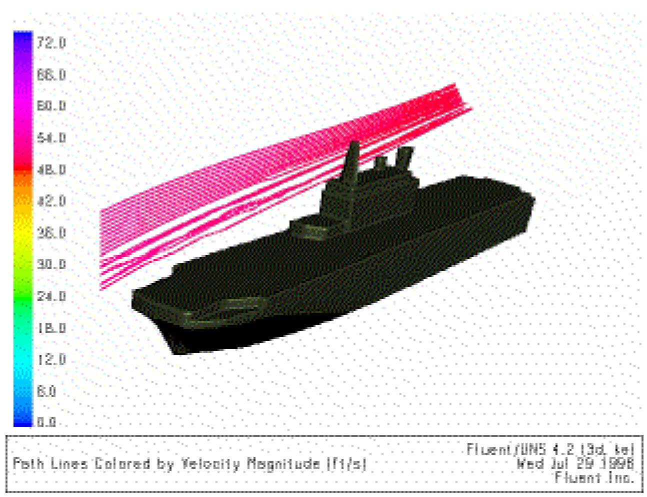


Figure 69. Animated gif showing airflow over ship (US Govt. image, courtesy of K. Long)

3.7.7 Audio

Some existing hazard warning systems for commercial aircraft use audible warnings, e.g. a bell or voice. Participants in our study were asked whether they would judge an audio indicator to be helpful or distracting. The consensus was against using audio. Pilots #1 and #2 were clear that they did not want the hazard indicator to have any audio component. Pilot #3 conjectured that a limited audio, such as a soothing female voice, might be helpful under certain limited conditions.

3.7.8 General Considerations

Other comments the pilots made were that the indicator should appear at the 180-degree point, the point in the approach where the pilot is abeam the intended landing spot facing downwind. The indicators should then either turn off as the wheels cross the deck, or remain on throughout the landing. For yellow (caution indicated, but controllable) conditions, it was thought potentially helpful to leave the hazard indicator on display, as the pilot might choose to fly into the indicated area (the "curtain"). Numeric indicators representing airflow speed were not preferred; the pilots stated that they wouldn't have the time to read numbers as they approached the landing spot. All of the pilots preferred an idealized representation rather than exact visualization of airflow, again in the interest of keeping the display simple. One pilot suggested just painting the deck or the landing spot red or yellow. It was also suggested that more detailed options might be useful at the start of the approach. Perhaps a more complex visualization with wind arrows or airflow lines could be selected by the pilot at that point, fading to a simpler version as the pilot flew closer. It was also pointed out that it was important for the system to be credible, with no false positives or negatives. Finally, it was critical that the pilot be able to turn the system on and off, and that a vernier control be present to adjust the brightness of the display based on the ambient light.

3.8 Conclusions

A preliminary usability study of an airflow hazard visualization system for helicopter pilots landing on board a moving ship indicated that pilots would use such a system if it were available on their aircraft. They expressed a need to know more about airwake hazards and a desire to have the information presented to them in the cockpit as they were landing. The preference was for a head-up display with “scene-linked” [66] indicators vs. an instrument panel display.

The pilots indicated that any airflow hazard symbology should present the minimum critical information such as location of the hazard and whether it was a warning (yellow) or danger (red). There was no desire for detailed quantitative information or even qualitative information such as type of hazard such as vortex, downdraft, turbulence, wind shear, etc. In other words, what the pilots are looking for is a decision support system, not a scientific visualization system, and any future work in this area should be done with this kept in mind. They want to be shown the effects – e.g. hazards to aircraft – and not causes – e.g. this is a vortex caused by the wind curling up and over the deck edge with downdrafts of up to 400 ft/minute. Extensive detail, motion, complex shapes, too many colors, were all considered too distracting and possibly dangerous in the high-demand environment of shipboard helicopter operations. Preference was strongly given to static rather than dynamic indicators. Concerns were expressed over distractions such as motion inducing vertigo, confusing symbology causing doubt in the pilot's mind, etc. Nevertheless, there was a clear desire to have such a system in the cockpit.

3.8.1 "The Holy Grail"

We close this chapter with a quote from one of the pilots in our usability study, asked if he thought a system of airflow hazard visualization might have the potential to improve helicopter flight safety:

"...[This system] offers … a chance to avoid mishaps that have happened before, combined with the opportunity to provide a greatly expanded operating envelope…

"That's the Holy Grail… to be able to both increase safety and increase operational capability at the same time. Usually you don't find something with the potential to do both. Usually you either have something that makes it a lot safer but tends to impose certain operational restrictions…or you have something that gives you greater operational capability but there's risks associated with employing that additional capability... In this case you actually have a concept that could potentially give you both."

Chapter 4 ■

Flight Simulation Study

4.1 Introduction

In this chapter we discuss in detail the system implementation, experiment setup, protocol, results, and data analysis from the flight simulation usability study. Section 4.2 describes the process we followed in implementing the system, including the choices we made in selecting the hazardous scenarios and during implementation. Section 4.3 then describes the usability study itself, and how the study was designed to carefully examine the measures related to the hypotheses under test. We discuss the simulator parameters we used to set up the approaches, and the landing difficulty levels we chose in order to verify each of our hypotheses. We describe the physical setup of the simulation, the technical specifications for the equipment used, and validation of its quality.

Finally, in section 4.4, we give the results of the experiment, discussing our hypotheses and the extent to which they were confirmed by the data. In the section on

Primary Results, we analyze the key data related to our main hypotheses, and discuss the choice of statistical methods as related to the experiment design. The large amount of data collected also permitted several areas of data analysis, which we discuss in the Ancillary Results section. These ancillary results are not necessary for validating the main hypotheses, but are generally compatible with them, and suggest avenues for further research.

4.2 Implementation of Flight Simulation Interface

With the knowledge gained from the results of the low-fidelity prototype study, we implemented a version of our interface in Advanced Rotorcraft Technology's (ART) high-fidelity rotorcraft simulator [1], a fixed-base, aerodynamically accurate flight simulator with a three projection screen display (Figure 70). Their visual subsystem was layered on top of OpenGVS [91], an OpenGL-based [83] scene manager built by Quantum3D. As a result, we could generate complex three-dimensional OpenFlight [75] objects in MultiGen software, import them into ART's flight simulator graphics subsystem, and manipulate them as desired in the flight simulator scene. OpenGL is an industry-standard API for developing 2D and 3D graphics applications. OpenFlight is a commercial, hierarchical 3D scene description file format, based on OpenGL, which is widely used in the flight simulation industry.

Figure 70. ART flight simulator with pilot in front of projection screen and operator at rear console

4.2.1 Design and Implementation Process

We used a three-phase iterative design process in developing the interface and the study protocol. Highly detailed and realistic 3D models of a Sikorsky UH-60 Seahawk helicopter (Figure 71) and a Navy LHA (Tarawa-class) ship (Figure 72) had already been input into the flight simulator system.

Figure 71. Sikorsky UH-60 Seahawk helicopter (US Govt. image, http://www.arc.nasa.gov)

Figure 72. LHA steaming, loaded with aircraft (US Govt. image, courtesy of K. Long)

In the first phase, we spent an extensive amount of time studying and analyzing a large amount of Navy Dynamic Interface (DI) helicopter-shipboard flight test data for the H-60 and LHA. An experienced Navy flight test engineer assisted us in selecting four critical scenarios where, depending on the speed and direction of the wind over the ship deck, hazardous airflow could occur (Figure 73).

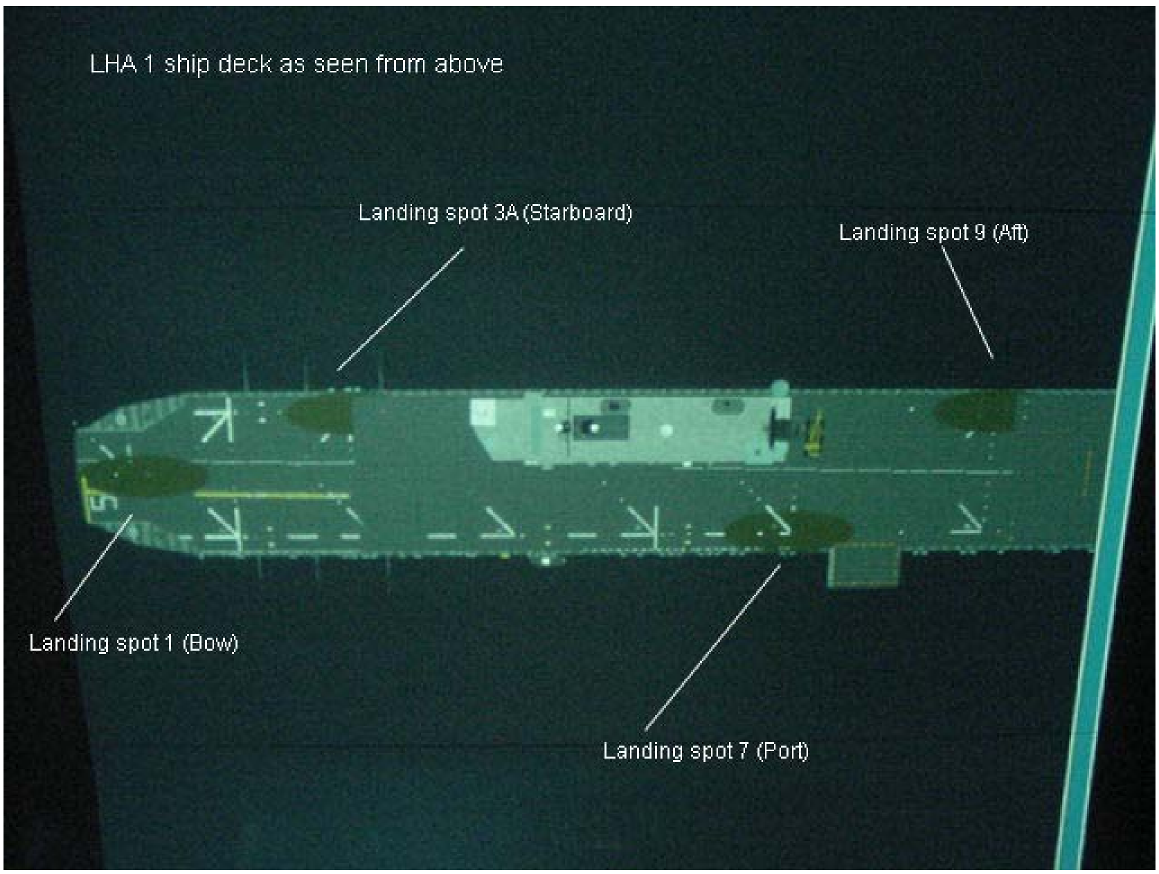


Figure 73. Photo from ART flight simulator, labeled: landing spots and hazard locations for the four scenarios on the LHA-1 ship

We defined a "scenario" as a combination of wind direction and approach to a landing spot (the LHA had ten different landing spots) where hazardous airflow could occur near or over the chosen landing spot (Table 2). In situations similar to these, accidents had occurred in the past. We planned to vary the wind speed and turbulence level for each scenario to create four "configurations" that would yield approaches of the four different landing difficulties. A "configuration" was defined as a combination of a scenario and a wind over deck speed and turbulence level (wind over deck is the vector sum of the ambient wind vector and the ship's motion). We later ended up using the terms "configuration" and "approach" interchangeably during our study, as each configuration was in one-to-one correspondence with an approach.

Table 2.

Simulator Scenario Descriptions[1]

Scenario	Approach Configuration	Landing Spot	Wind Direction	Wind Speed	Problem Description	Problem Location and Size	Expected Problem Manifestation
Starboard	S1	3A	030 degrees	Low	Upwelling over deck edge; downdraft inboard and outboard of deck edge	Low Hover, near landing spot center	Outboard deck edge: High torque required = suckdown Deck edge: Low torque required/ballooning Inboard deck edge: High torque required = suckdown
	S2			Medium			
	S3			High			
	S4			Extreme			
Aft	A1	9	360 degrees	Low	Elevated large scale turbulence intensity aft of island to aft edge of ship	Directly aft of island from deck up to above island height	Elevated control workload in all axes, esp tail rotor and lateral
	A2			Medium			
	A3			High			
	A4			Extreme			
Port	P1	7	330 degrees	Low	Longitudinal vortex inboard of deck edge at rotor height	Inboard of deck edge at low hover heights	Excessive lateral and directional control requirements; added turbulence with upwind aircraft
	P2			Medium			
	P3			High			
	P4			Extreme			
Bow	B1	1	360 degrees	Low	Strong downwash in recirculating bubble; upwash at fwd edge of bubble	Downwash aft of spot, upwash fwd of spot	Suckdown/added torque req'd aft of spot Ballooning/lower torque req'd fwd of spot
	B2			Medium			
	B3			High			
	B4			Extreme			

Notes:

1. Ship, Course, Speed, Sea State, Temperature, Ship Motion, Gross Weight, Loading are identical for all scenarios. Ship Course is directly to North or 360 degrees.

We then input actual airflow data from Navy DI flight tests, computational fluid dynamics (CFD) calculations, and wind tunnel tests into the simulator. We estimated wind conditions that would create approaches with landing difficulties from PRS 1 to PRS 4 for each ship/wind-direction scenario. Then we stored each approach configuration as a checkpoint in the simulator and gave it a code number or “Case ID”

(Figure 74). We reserved simulator time and invited a Navy pilot to test-fly all the stored approaches to verify the realism of the simulation, the location of the areas of hazardous airflow, and the validity of our landing difficulty ratings.

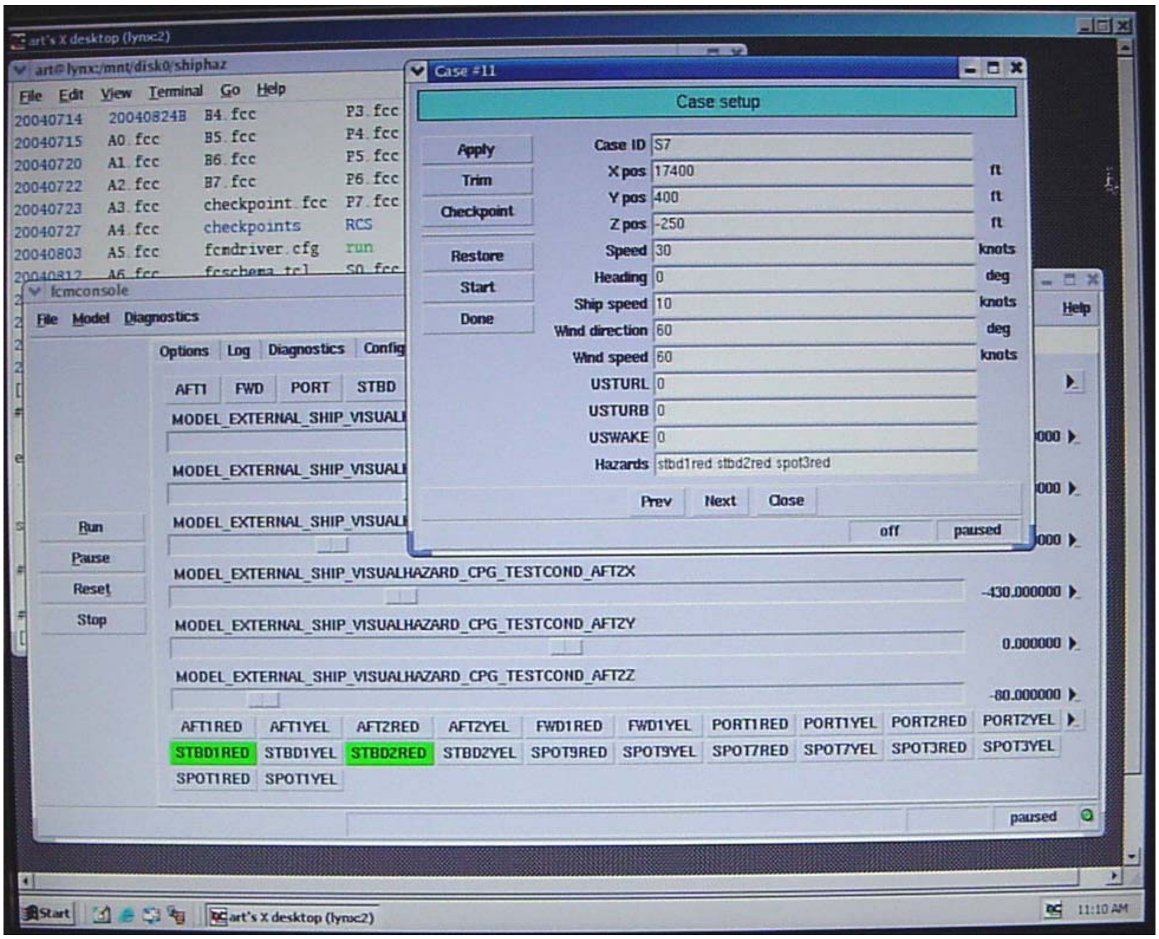


Figure 74. ART simulator interface: checkpoint for starboard approach with high winds and hazard indicator visible

For the second phase, based on the test pilot's input and after lengthy examination of the airflow data, we created translucent 3D OpenFlight surfaces that outlined the volumetric regions of hazardous flow (Figure 75). (Actual surfaces were more translucent than pictured in the figure.) Based on the results from the study of the low-fidelity prototype, we had selected a simple, static design for the hazard indicators and used only two colors, yellow (caution) and red (danger). The shape and appearance of the indicators were chosen to indicate the physical location of the hazard without undue distraction and without duplicating any symbology used for other purposes, while the color meanings are conventional and widely accepted in the aviation world.

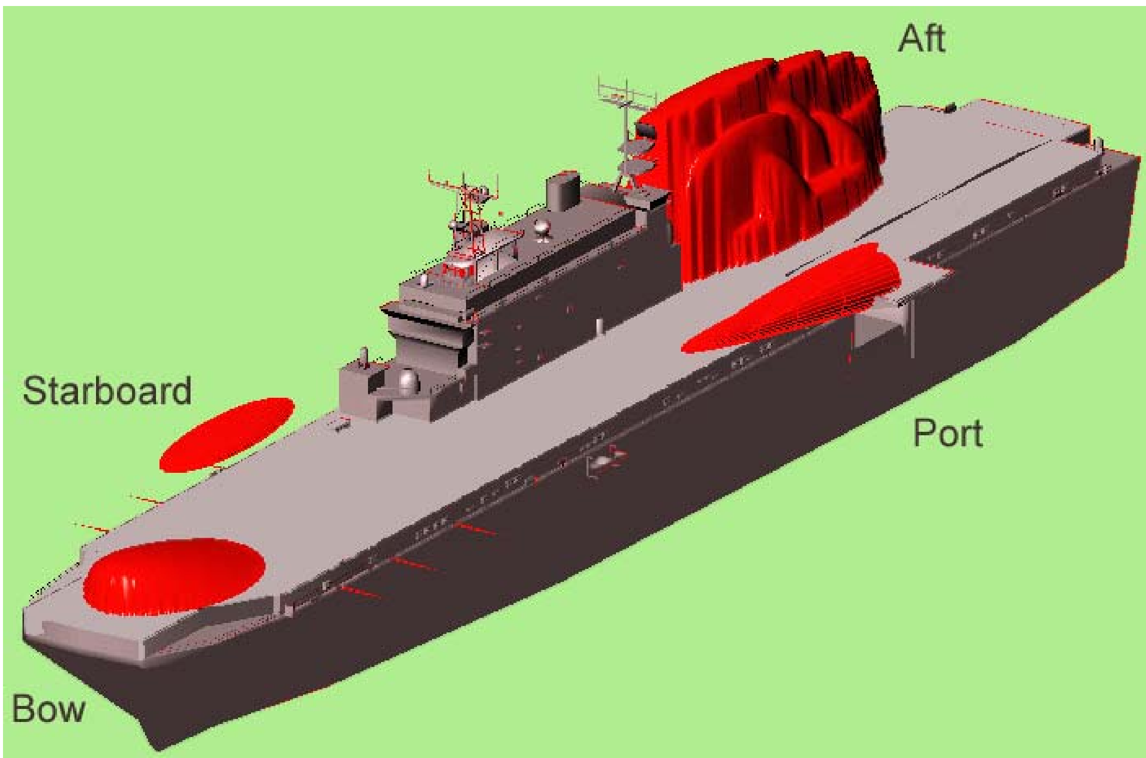


Figure 75. Visual hazard indicators used in the study for the four scenarios, Aft, Bow, Port, and Starboard (actual indicators were more translucent than depicted)

The boundaries of the hazardous areas were determined upon extensive review of the archived airflow data from flight tests and consultation with a Navy flight test engineer. The degree of transparency of the hazard indicator objects was set at the level of transparency (approximately 70% in Rhino3D) preferred by pilots during their evaluation of the low-fidelity prototype.

We then imported the objects into the simulator's visual subsystem, scaling, rotating, and translating them into their proper positions on the LHA. This was done manually in order to accurately correlate the surfaces with the known areas of hazardous airflow from our study of the data. The objects were linked to the ship so that they seemed to be part of the simulated outside world; they appeared as clouds or curtains hovering over particular locations on shipboard. This is an accurate model of shipboard airwake; any hazardous areas produced by wind blowing over ship structures will move along with the ship.

The following figures (Figure 76)(Figure 77)(Figure 78)(Figure 79) are digital photos taken in the simulator room at Advanced Rotorcraft Technology, Inc. (ART) that depict the visual appearance of each of the four hazard indicators for each of the Aft, Bow, Port, and Starboard scenarios. The yellow (caution) indicators are shown; the red (danger) indicators were identical except for their color. The images appear somewhat grayed out on the projection screen but were still clearly visible to the pilot flying the approach.

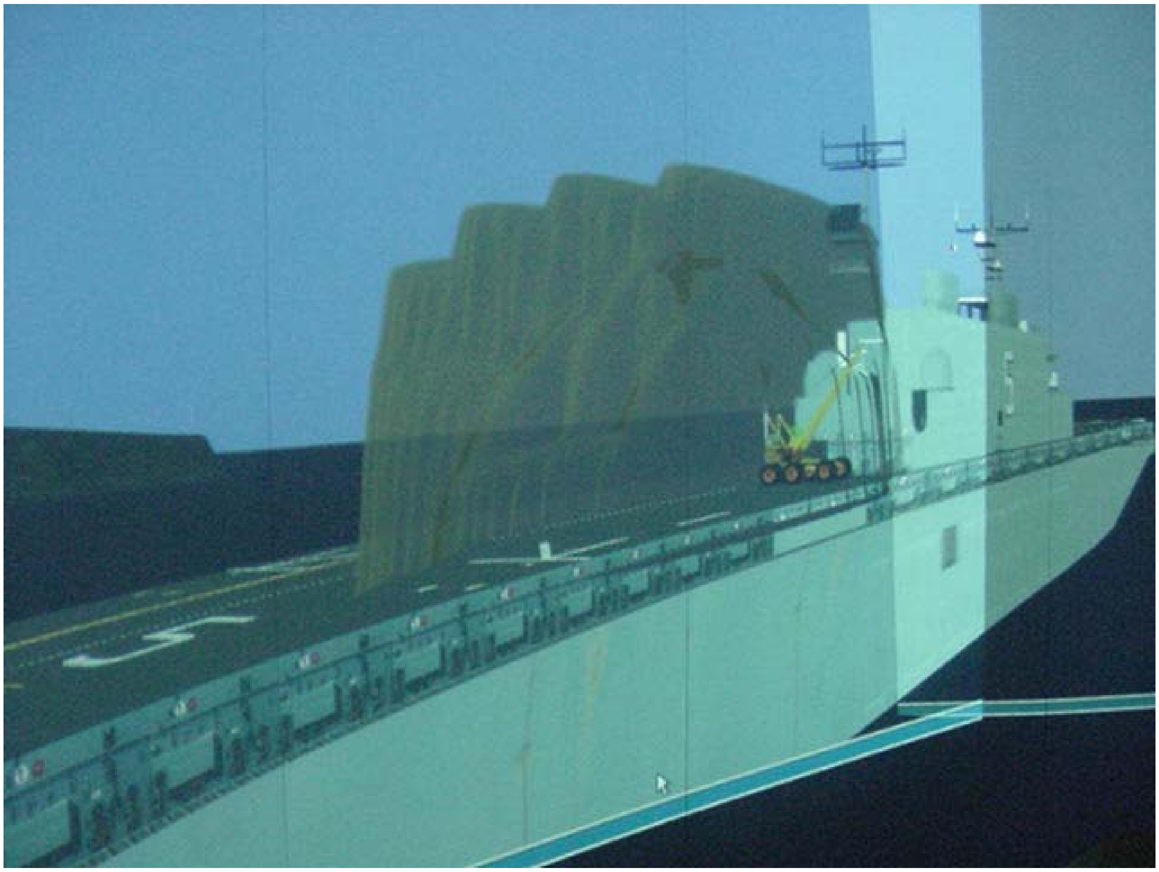


Figure 76. Hazard indicator (yellow, caution) - Aft scenario

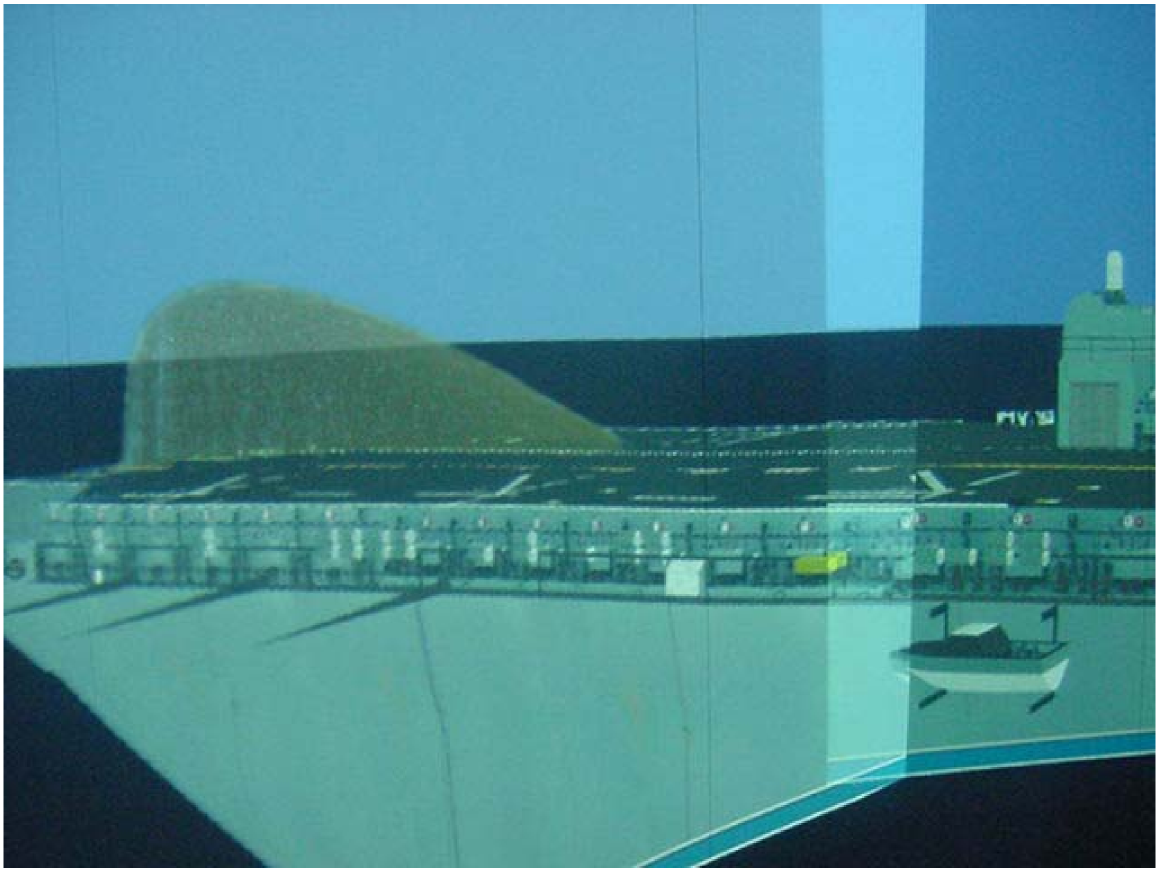


Figure 77. Hazard indicator (yellow, caution) - Bow scenario

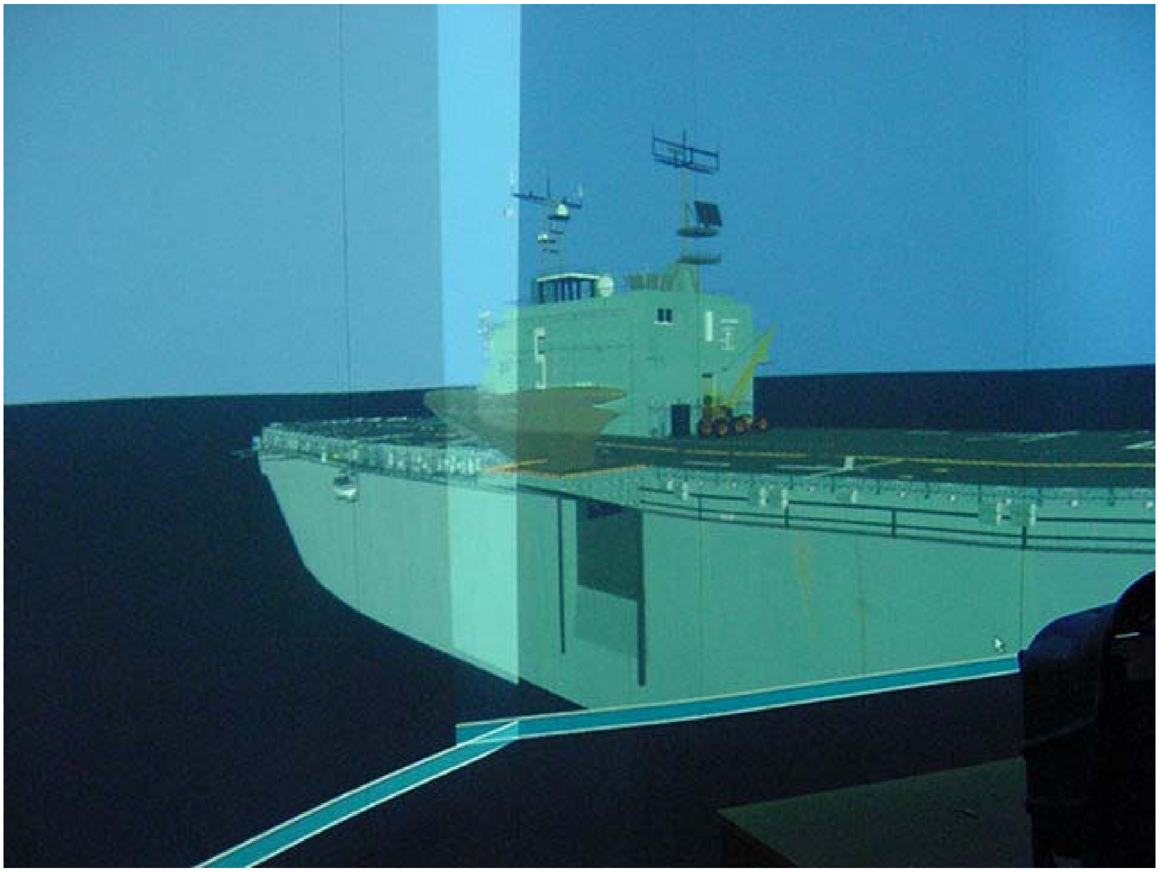


Figure 78. Hazard indicator (yellow, caution) - Port scenario

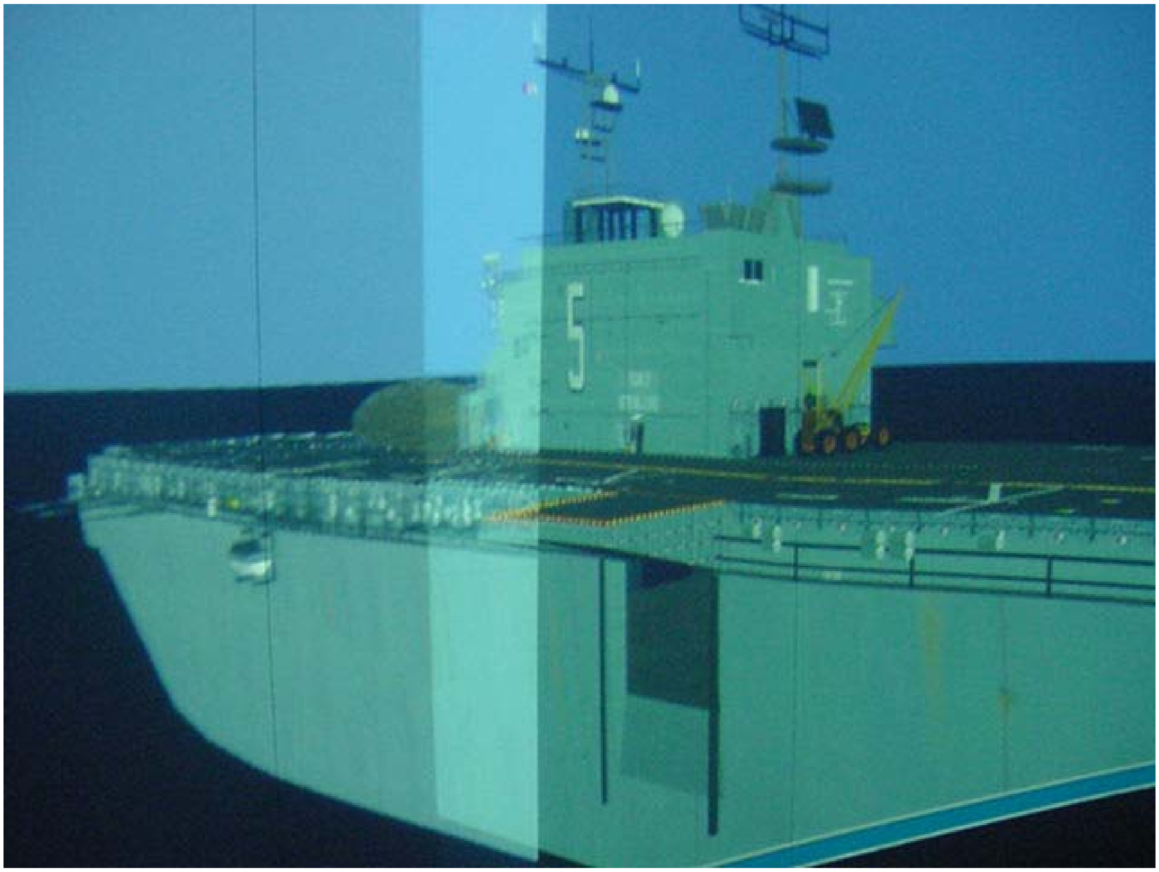


Figure 79. Hazard indicator (yellow, caution) - Starboard scenario

Finally, we reserved more simulator time and recruited an experienced Navy test pilot to fly all the approaches and perform a final verification of the correct placement of the hazard indicators as well as the validity of the stated difficulty levels of the approach. He came back a second day after we fixed bugs found on the first day.

At this point, we were confident that we had a set of realistic, aerodynamically accurate approaches for helicopter pilots landing on an LHA ship. We checkpointed all 28 different approaches, plus four practice approaches with light winds for the orientation flight, over four scenarios in preparation for our flight simulation usability study (Table 3) (Figure 80).

Table 3. Table of 32 approaches with simulator variables for each approach. 28 approaches were used in the study; 4 approaches (A0, B0, P0, S0) with light winds were designated practice approaches and data was not recorded for them.

Airflow Hazard Visualization Study
Approach Configurations* and Scenarios**
May - September 2004

Approach Number	Approach Code	Scenario Name	Landing Spot	Initial Location	Ship Speed	Wind Direction	Wind Speed	Hazard Name	Landing Difficulty	Comments
1	S0	Starboard	3A	(-2600,+400,-250)	10 kts	0 degrees	0 kts	none	1	Practice approach, start or
2	A0	Aft	9	(-2600, 0, -250)			0 kts	none	1	Practice approach, start di
3	P0	Port	7	(-2600, -300, -250)			0 kts	none	1	Practice approach, start or
4	B0	Bow	1	(-2600, -200, -250)			0 kts	none	1	Practice approach, start or
36	S1	Starboard	3A	(-2600,+400,-250)	10 kts	60 degrees	0 kts	none	1	Appch from starboard
40	S2						30 kts	none	2	
26	S3						40 kts	none	3	
22	S4						60 kts	none	4	
28	S5						30 kts	stbd_yel	2	
30	S6						40 kts	stbd_yel	3	
38	S7						60 kts	stbd_red	4	
31	A1	Aft	9	(-2600, 0, -250)	15 kts	0 degrees	40 kts	none	1	Appch from aft
20	A2							none	2	
25	A3							none	3	
29	A4							none	4	
42	A5							aft_yel	2	
37	A6							aft_yel	3	
33	A7							aft_red	4	
23	P1	Port	7	(-2600, -300, -250)	10 kts	negative 60 deg	10 kts	none	1	Appch from port
46	P2						15 kts	none	2	
45	P3						15 kts	none	3	
35	P4						30 kts	none	4	
47	P5						15 kts	port_yel	2	
44	P6						15 kts	port_yel	3	
27	P7						30 kts	port_red	4	
39	B1	Bow	1	(-2600, -200, -250)	15 kts	0 degrees	0 kts	none	1	Appch from port
43	B2						15 kts	none	2	
34	B3						30 kts	none	3	
41	B4						55 kts	none	4	
21	B5						15 kts	fwd_yel	2	
32	B6						30 kts	fwd_yel	3	
24	B7						55 kts	fwd_red	4	

*Approach configuration refers to a particular combination of start position, landing spot, wind azimuth and speed, ship speed, hazard
**Scenario refers to a fixed set of 1. Start position, 2. Landing spot, 3. Wind azimuth 4. Ship speed
***Initial helicopter airspeed is always 30 kts

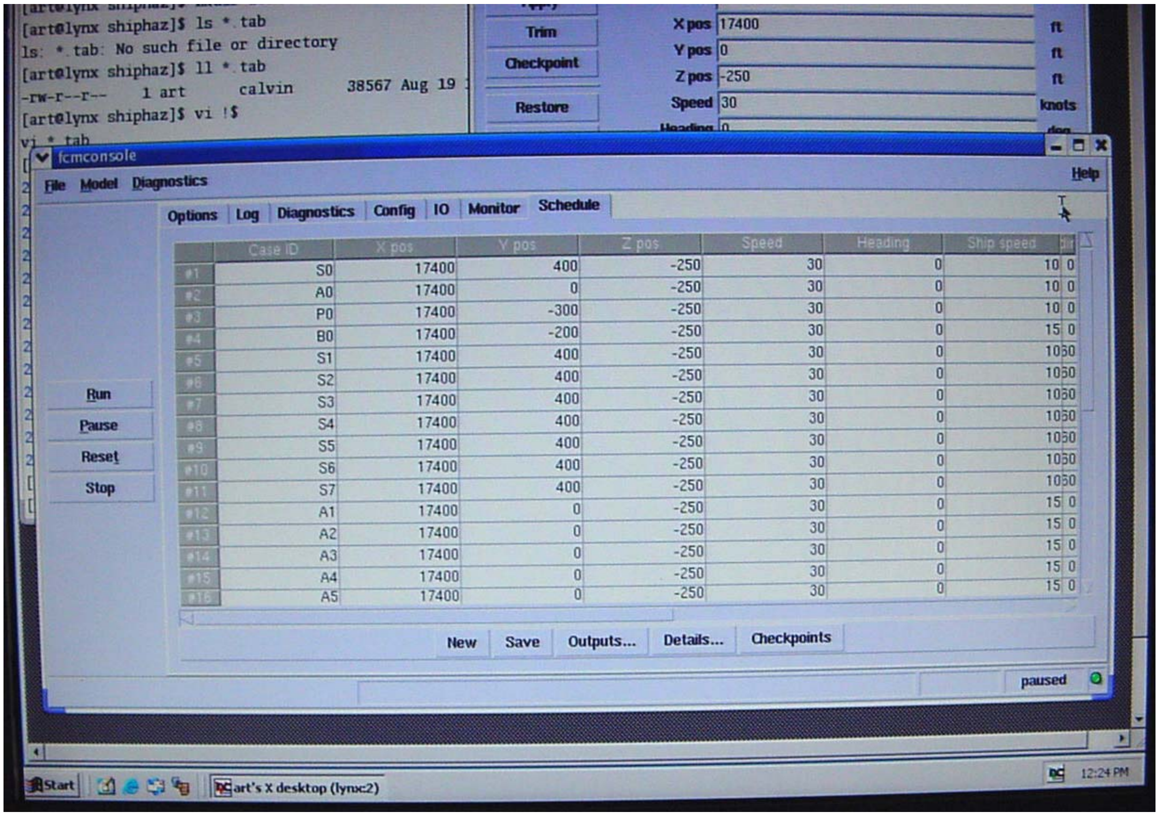


Figure 80. ART simulator interface for entering checkpoints for a set of approaches

The third and last phase was the final usability study, which is described in detail in the following sections.

4.3 Flight Simulation Study

In order to produce a high-quality usability study of a specialized interface, it is important to select participants who are domain experts. That is, the quality and relevance of the results depend on getting people who actually fly under the demanding conditions that we hope to duplicate in this study. To test our hypothesis that the presence of a visual hazard indicator could improve helicopter flight safety, we recruited sixteen experienced helicopter pilots to participate in the flight simulation study.

4.3.1 Study Overview and Issues

The use of a flight simulator in any study immediately raises an issue of realism. Our study was designed for as high a level of technical fidelity as possible, and also to establish the correct mood for the testing. Using a simulator is, of course, not as stressful as the actual flight situation. However, during our pre-flight briefing, we made a special effort to ensure the pilots would use the same judgments they would in the real world. "If you feel the controllability of the aircraft is in question, follow the same safety procedures as you would in the real world." Although it is impossible to verify whether this proscription was followed absolutely, comments gathered from the pilots during the simulation and observation of the pilots' behavior during the simulation (the intensity of their gaze, grip on the controls, sweating, breathing levels, etc.) indicated that they were taking it seriously and not thinking of it as, for example, a video game. Additionally, pilots are generally quite conscious of the fact that lives depend on their proficiency and decision-making during the critical moments of a flight, and take pride in their skills and their ability to consciously marshal their skills even under moments of extreme duress. Although we were clear that the purpose of the study was to test the hazard display system rather than the pilot, the pilots' awareness that the test was being observed would reasonably be expected to stimulate that pride in their skills. For these reasons, we believe the results of our simulation fairly accurately reflect results that would have been achieved in the real world.

For safety-critical applications, simulation will often be necessary. Experiments designed to test interfaces for use under such conditions must try to recreate environmental factors such as stress, responsibility, fatigue, etc. A high degree of realism must be maintained during the usability tests for this reason.

Consistent with our efforts to accomplish this, we chose a high fidelity, realistic helicopter flight simulator with accurate aerodynamic models, which we then provided with actual airflow data from shipboard flight tests. The pilots sat in an aircraft seat with full helicopter controls (cyclic, collective, and tail rotor pedals) with force feedback, in front of a cockpit instrument panel, and viewed visuals on three large projection screens. The pilots flew simulated final approaches to land a Sikorsky H-60 helicopter on a moving ship (an LHA or "Tarawa-class" Navy amphibious assault ship) under different wind conditions, some of which entailed airflow hazards such as vortices, downdrafts, or turbulence on or near the landing site. Four different landing difficulty levels were used. Other than the control approaches (no hazard present), each approach was flown twice by each pilot, once with a hazard indicator present and once without. Data was gathered both objectively from the flight simulator's recording capability and subjectively from a Likert-scale questionnaire administered to the pilots after the test.

4.3.2 Study Protocol and Design

The study was a 3 (landing difficulty) x 2 (presence or absence of visual hazard indicator) x 4 (approach type) + 1 x 1 x 4 (control) within-subjects design. Each pilot flew the same 28 simulated approaches, but in different orders. Four different approach scenarios were selected where winds could create a hazard to helicopters landing on the deck of a Navy ship. As described in section 4.2, a flight test engineer with 17 years of experience with Navy shipboard helicopter flight testing assisted us in designing the four scenarios, selecting various wind speeds and turbulence levels for each scenario to create approaches with different landing difficulty levels, and determining where hazardous airflow conditions would exist. We then recruited a second experienced Navy helicopter test pilot who flew all the approaches in the simulator and evaluated the correctness of the landing difficulty level and the correct placement of the hazard indicators.

Each participant received a pre-flight briefing that explained the structure of the simulation and the use of the controls of the simulator and instructions as to the meaning of the yellow and red hazard indicators. Participants then performed a series of orientation flights before beginning the actual test. There were five orientation flight sequences. First, pilots were given a few minutes to accustom themselves to the "feel" of the simulator by flying the simulated helicopter from a low speed up to cruise and back down to a hover, and then flying around the ship and simulated terrain. Then the pilot flew four approaches, one to each of the four targeted landing spots for the test scenarios, but with low (non-hazardous) winds. Thus they were familiarized with the environment and the out-the-cockpit view for each of the approach scenarios.

The dual purposes of the orientation flights were to accustom them to the feel of the controls of the simulator, and to determine if they had the skill level to be a credible participant in the experiment. Out of 17 pilots recruited for the study, one was unable to fly the orientation flights and was excused, leaving 16 pilots who then completed the test approaches.

At the outset of each approach, pilots were given wind direction but not wind speed. Revealing wind speed could introduce bias due to the pilots' assumption that wind speed correlates with landing difficulty level, although pilots were briefed that hazards could occur even at low wind speeds.

4.3.3 Approach Description

For each approach or run, the simulator was set to a previously saved checkpoint that positioned the helicopter at 250 feet above mean sea level and 2600 feet back of the stern of the ship. Wind and turbulence conditions that would produce a landing of difficulty 1-4 had been previously programmed into the simulator, and the appropriate hazard indicators were turned on at the beginning of the approach (if an indicator was supposed to be present). The simulator flight controls were trimmed to a 30-knot airspeed, and the pilots were given a verbal clearance to land on one of four landing spots and the wind direction. The pilots were asked if they were ready, and then the simulator was set running. Pilots flew until the landing was complete, they verbally called out an aborted approach, or they crashed. Then the simulator was stopped and set up for the next run. Pilots were encouraged to make verbal comments during the test, and the entire test was videotaped for all pilots. The video camera was positioned behind the pilot, facing the projection screens, so that the pilot would not be visible on the tape.

4.3.4 Approach Scenarios

Scenarios were labeled based on which landing spot the pilot would be cleared for and where the airflow hazard would occur under certain wind conditions. More details on the selection and implementation of the scenarios were presented in section 4.2.1 (Figure 75).

Scenario A ("Aft"): Direct stern approach to landing spot 9, the aft-most landing spot on the LHA. With a direct bow wind, and at high wind speed and turbulence levels, an airflow hazard would occur downwind of the ship superstructure over landing spot 9.

Scenario B ("Bow"): A 45-degree approach to the most forward spot on the bow of the ship, spot 1, and winds directly from the bow. This created an area of heavy downdraft ("suckdown") directly over spot 1, which was often unexpected as it occurred even at relatively low winds and even in smooth wind conditions.

Scenario P ("Port"): A 45-degree approach to the port side of the ship, to landing spot 7, just forward of the elevator and next to the ship superstructure. Winds from 300 degrees (assuming the ship is moving toward the north or 360 degrees) caused a rotor to form over the deck edge just over landing spot 7. Again, this hazard formed even at relatively low winds.

Scenario S ("Starboard"): A 45-degree approach from starboard to landing spot 3A just forward of the ship superstructure. When winds are from 60 degrees, a vortex forms just at the deck edge and beside landing spot 3A.

4.3.5 Landing Difficulty Level

We used four different landing difficulty levels (Table 4) based on the Navy's Pilot Rating Scale of landing difficulty [136]. (Additional information on the Pilot Rating Scale was given in Chapter 2.) Each pilot flew each approach scenario at all landing difficulty levels. For each of LD 2 through 4, each pilot flew one approach with and one without a visual hazard indicator. For LD 1, each pilot flew one approach without a hazard indicator. Thus, each pilot flew 7 approaches in each of the 4 landing scenarios, a total of 28 approaches per pilot. The approaches were designed to take about 1-2 minutes each; therefore, the entire simulation took about one hour per pilot; this time length was designed to prevent pilot fatigue.

Table 4. Landing difficulty levels

Landing Difficulty	Definition	Approaches per pilot	Purpose
LD 1	No problems; minimal pilot effort required	4 w/o indicator	Control
LD 2	Moderate effort required; most pilots able to make a safe landing consistent with some effort	4 w/o indicator + 4 with indicator	Test negative effects of hazard indicator
LD 3	Maximum pilot effort required; repeated safe landings may not be possible	4 w/o indicator + 4 with indicator	Test benefit of hazard indicator
LD 4	Controllability in question; safe landings not probable under these conditions	4 w/o indicator + 4 with indicator	Test benefit of hazard indicator with pilot instructional procedure

4.3.5.1 Landing difficulty 1 (LD 1) – Control

These approaches showed how well the pilot could operate the simulator in the absence of particular hazards, and also provided periods of rest to the pilots to reduce fatigue and avoid discouragement (since the test consisted of an abnormally high percentage of very challenging landing conditions).

4.3.5.2 Landing difficulty 2 (LD 2)

Testing for negative effects of the hazard indicator. This difficulty level required moderate pilot effort. The hazard indicator (if present) was a translucent yellow object outlining the area where turbulent flow could be found. Because the conditions at LD 2 are considered to be within normal pilot abilities, we would expect few crashes even without the hazard indicator. The hypothesis tested at LD 2 was that the hazard indicator would not increase the crash rate (e.g. by distracting the pilot). Pilots were instructed that the yellow hazard represented caution and that they could continue the approach.

4.3.5.3 Landing difficulty 3 (LD 3)

Testing for benefit of hazard indicator. This difficulty level required maximum pilot effort. The hazard indicator was the same type as for the LD 2 approaches. Pilots were told that yellow represented caution and they were to continue the approach. A higher crash rate was expected at LD 3 commensurate with the more challenging conditions compared with LD 2. We hypothesized that the hazard indicator would reduce this crash rate – ideally, to a rate comparable to LD 2.

4.3.5.4 Landing difficulty 4 (LD 4)

Testing for benefit of hazard indicator with pilot instructional procedure. At LD 4, safe landings were not probable. Fifteen pilots were told that if they detected a red hazard indicator along their approach path, standard operating procedure (SOP) was to abort the landing immediately. (The sixteenth pilot, who was not initially given this instruction, spontaneously proposed that it should be standard operating procedure.) These approaches test whether the same hazard indication methodology used for reducing the crash rate in marginal conditions will also operate reasonably in extreme conditions.

4.3.6 Order of Presentation

To compensate for possible learning effects, half the pilots flew scenarios A and P without the hazard indicators and scenarios B and S with the hazard indicators during the first half of the test, and then conversely for the second half. The other pilots flew scenarios A and P with hazard indicators and scenarios B and S without indicators during the first half of the test. This was accomplished by defining an approach order randomly within these constraints, then reversing it to create a second order, then switching the first and second halves to create a third and fourth order. It was chosen so that the most difficult approaches would not all follow one another, to reduce the likelihood of pilot fatigue. (Table 5) lists the approach orders. Rows indicate order of presentation. Within the rows, the order is random. In the cells, numbers represent landing difficulty, followed by presence (H) or absence (-) of hazard indicator, e.g. “3-” in column “B” indicates an approach to the Bow spot at LD 3 and no hazard; “2H” in column “A” indicates a run to the Aft spot at LD 2 with hazard indicator present. LD 1 (control) runs were scattered randomly through the series so each pilot flew 28 runs.

Table 5. Simulated Approach Orders

Order 1 (4 pilots)				Order 2 (4 pilots)			
A	P	B	S	A	P	B	S
2-	4-	2H	4H	2H	3H	2-	3-
3-	2-	4H	3H	3H	4H	4-	2-
4-	3-	3H	2H	4H	2H	3-	4-
4H	2H	3-	4-	4-	3-	3H	2H
3H	4H	4-	2-	3-	2-	4H	3H
2H	3H	2-	3-	2-	4-	2H	4H
Order 3 (4 pilots)				**Order 4 (4 pilots)**			
A	P	B	S	A	P	B	S
4H	2H	3-	4-	4-	3-	3H	2H
3H	4H	4-	2-	3-	2-	4H	3H
2H	3H	2-	3-	2-	4-	2H	4H
2-	4-	2H	4H	2H	3H	2-	3-
3-	2-	4H	3H	3H	4H	4-	2-
4-	3-	3H	2H	4H	2H	3-	4-

4.3.7 Dependent Variables

During the simulation, 50 variables such as velocity and position of aircraft in x, y, z, control stick position both lateral and longitudinal, collective and pedal positions, landing gear forces, etc., were collected by the flight simulator at 10 Hz and stored in data files labeled for each run and pilot. However, our primary dependent measure was the crash rate. A "crash" was defined as an impact with the ship's deck with a vertical velocity of 12 feet per second (fps) or greater as measured by the simulator. We chose this number because it is the Navy standard structural limitation for helicopters. In order to be certified for shipboard use in the US Navy, rotorcraft must be able to withstand an impact of 12 fps upon touchdown [60, 121, 122].

We also gathered subjective pilot opinions from a 21-probe Likert-scale (1-5) questionnaire administered to the pilots at the end of the simulation. For each probe, the pilots had to circle one of “Strongly Disagree” (1), “Disagree” (2), “Neither Agree Nor Disagree” (3), “Agree” (4), and “Strongly Agree” (5).

4.3.8 Hypotheses

We tested four hypotheses:

1. Crash rate will be reduced by the presence of hazard indicator (LD 3).

2. Crashes will be eliminated by red hazard indicator if a standard operating procedure (SOP) is given to the pilots (LD 4).

3. Hazard indicator will not cause distraction or degradation in performance in situations where adequate performance is expected without indicator (LD 2).

4. Pilots will say they would use airflow hazard visualization system.

4.3.9 Participants

We recruited 17 military and civilian helicopter pilots by word-of-mouth and through emailed requests for volunteers. 16 pilots (1 female) flew the orientation flights successfully and completed the simulation test. This group of pilots had no previous experience on the simulator used in the experiment and had not seen or heard of any type of visual hazard indicating system before. Pilot experience ranged from 200 to 7300 helicopter flight hours with the median number of hours being 2250, from 2 to 46 years of experience as a helicopter pilot with the median 13 years, and were from 25 to 65 years old, with a median age of 36 (Table 6). All pilots had normal or corrected-to-normal eyesight and were not color-blind. The study took about two hours, of which about one hour was spent in the simulator, and pilots were not paid for their participation.

Table 6. Pilot Demographics

Pilot	Employer	Helicopter Hours	Age	Years of Experience	Number of Shipboard Landings
1	Coast Guard	800	30	3	40
2	Coast Guard	1500	28	5.5	60
3	Coast Guard	770	26	2.5	200
4	Coast Guard	420	26	2	30
5	Coast Guard	200	25	2	75
6	Coast Guard	5600	43	22	1000
7	NASA	3100	59	46	100
8	Air Force/Air National Guard	3000	37	18	18
9	Air Force/Air National Guard	1800	34	8	0
10	NASA	2500	65	35	302
11	Army, civilian	4300	56	34	6
12	Air Force/Air National Guard	2000	33	7	0
13	Army, NASA	7300	51	29	150
14	Air Force, NASA	4000	60	36	0
15	Navy, Marines	3200	41	18	1500
16	Marines	850	33	8	600

4.3.10 Equipment

The study was performed at Advanced Rotorcraft Technology, Inc. (ART) in Mountain View, California, a small rotorcraft flight simulation company specializing in rotorcraft non-linear dynamics modeling and analysis [1].

4.3.10.1 Simulator Validation and Quality

ART's aerodynamic models have been verified by the US Navy via stability and control techniques and frequency domain validation [43, 105], and Navy flight test engineers and pilots have stated that they are more aerodynamically accurate than other rotorcraft flight simulators currently available [60, 105].

The only formal criteria to validate the performance of a high fidelity rotorcraft dynamic flight model are those in FAA Advisory Circular 120-63, Helicopter Simulator Qualification [34]. ART's dynamic models do not fully meet the FAA Level D specifications (although they are very close in many areas). However, these criteria are intended for training simulations (for example, the aircraft cockpit must be faithfully depicted) and are not as relevant for our purposes (we do not need to train helicopter pilots but instead are looking for an aerodynamically accurate flight simulation). Additionally, the criteria are so difficult for rotorcraft simulators to meet (the error tolerance in measured rotorcraft data is often greater than the Level D specifications; for example, Level D requires that the torque error is within 3%, which also falls within the modern flight test measurement error range [105]), that there are no physics-based rotorcraft flight models available today that fully satisfy the FAA Level D requirements for rotorcraft [60].

4.3.10.2 Simulator Specifications

The study was performed in a high fidelity helicopter flight dynamics simulator with a single seat configuration, flight controls with force feedback, instrument panel, and a three-channel projection outside world visual system utilizing 3D Perception projectors to provide 1024 x 768 resolution at 1000 ANSI lumens. Visual rendering is done using ART software that supports rendering on OpenGL graphics cards using OpenFlight format visual databases. Image generation is done on PCs with graphic acceleration hardware that provides a 60 Hz update rate with full-screen anti-aliasing and a 188” horizontal by 54” vertical field of view on a 6.5-ft radius cylindrical screen.

An operator console provides full simulator control, monitoring of the visual system and instrumentation displays, initialization to saved reset points and arbitrary test conditions. Control loaders for the pilot’s controls are electric and are driven by software that interfaces the flight dynamics model to the control loaders and edits the force feel characteristics. Four sets of control loaders are used to drive the longitudinal cyclic, lateral cyclic, collective and pedal controls. Computer generated images are rendered of the instrument panel. A dual 1.9GHz AMD processor computer with two graphics boards, located in the operator console, is used to drive a flat panel display that is mounted behind instrument panel overlays (Figure 81).

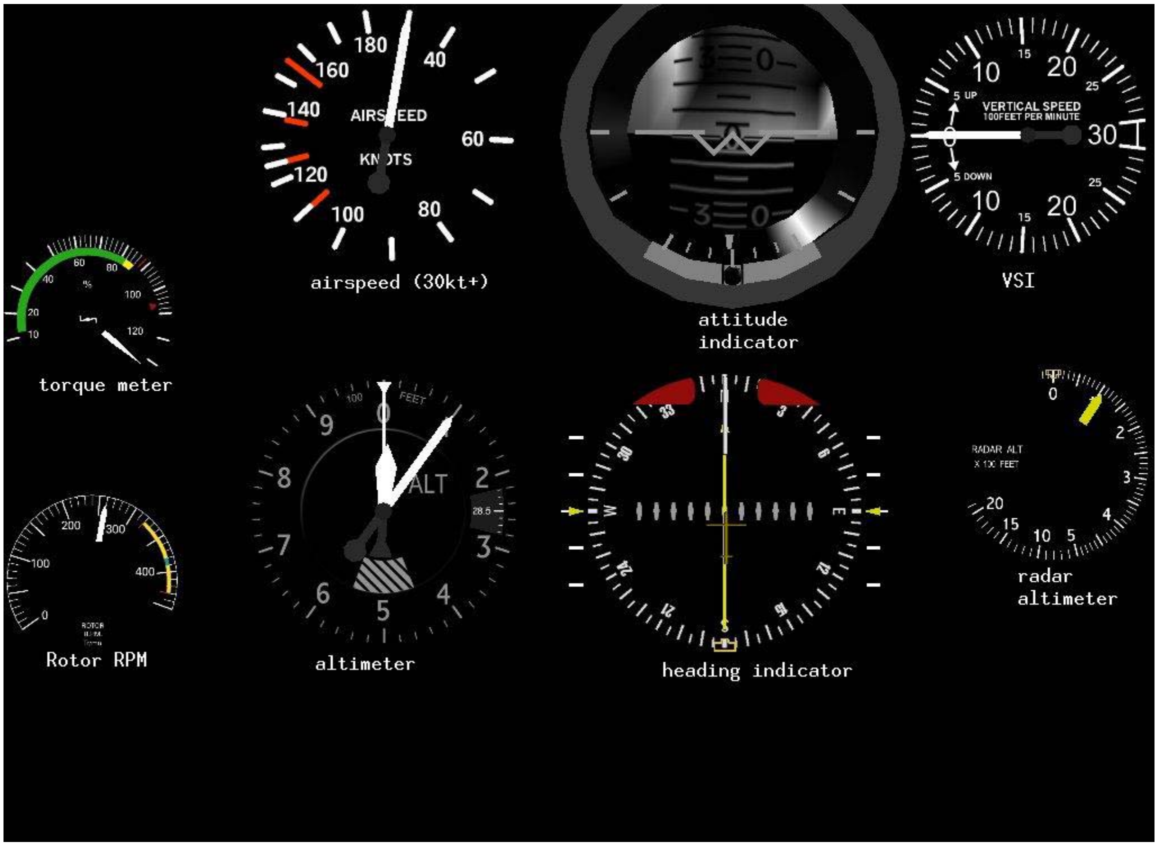


Figure 81. ART simulator instrument panel

4.4 Results

Below we discuss how the structure of the test data supports direct application of a relatively more powerful statistical test than could be used for non-experimental (e.g. population) data. We then present our primary results, showing that use of our system leads to a significant decrease in crash rate for a critical class of landings (those where landing is permitted, but difficult). Finally, we present additional data analysis, including other flight statistics and subjective data, such as pilot comments. These ancillary results, while generally supporting the primary conclusions, also suggest directions for further research.

4.4.1 Choice of Tests for Statistical Analysis

The statistical test we applied to most of our crash-rate hypotheses was the "paired two-sample t-test for means." In this section we explain why we chose to use the t-test and not the more general ANOVA procedure.

ANOVA is a generalization of the t-test for when there are multiple categories in which a contrast is hypothesized, different populations in different categories, or more than one variable tested simultaneously.

A common procedure is to apply ANOVA as a screening test and then, if a significant difference is detected, to apply t-tests to specific contrasts to locate the factor(s) responsible for the difference detected by ANOVA. The rationale is that if many t-tests are applied for detecting essentially the same type of difference in several sample sets, some of those t-tests will locate differences merely by coincidence, whereby the procedure would overestimate the significance of the difference.

In our study, we do not have the multiple categories or varying populations that would make a t-test inappropriate and require the more general ANOVA procedure. The test data has been structured so that the assumptions required for a t-test are valid. We are hypothesizing a difference in crash rate only for landing difficulty 3. Additionally, within each landing difficulty, the data is so structured that it is possible to pair the samples where in each pair, all variables are held constant except the presence or absence of the hazard indicator. This paired design allows the application of a paired-sample t-test. Conversely, unpaired t-test and ANOVA are inappropriate for a paired design, because they assume independence of the sample populations, which is not the case in a "before and after" test.

(For an example of where a paired-sample t-test is appropriate, consider measuring the difference in the height of humans with and without shoes. If the shod and barefoot populations are compared by unpaired t-test or ANOVA, the difference might very well be insignificant, as most height differences are due to other factors. However, if pairs of samples are obtained from each test subject, once with and once without shoes, a paired-sample t-test will correctly detect the difference in means between the two sets. [61, 68, 100])

The p values given are for the one-tailed distribution because the test hypotheses are directional (crash rate reduced or not increased).

4.4.2 Primary Results

This section presents the data analysis that supports our primary conclusion.

4.4.2.1 Summary of Crash Statistics

This subsection describes the overall crash statistics for our experiment, where, as explained earlier, a "crash" was defined as an impact with the ship's deck of more than 12 feet per second. (Table 7) summarizes all the data, and the following sections describe further statistical analysis of the data and our interpretations.

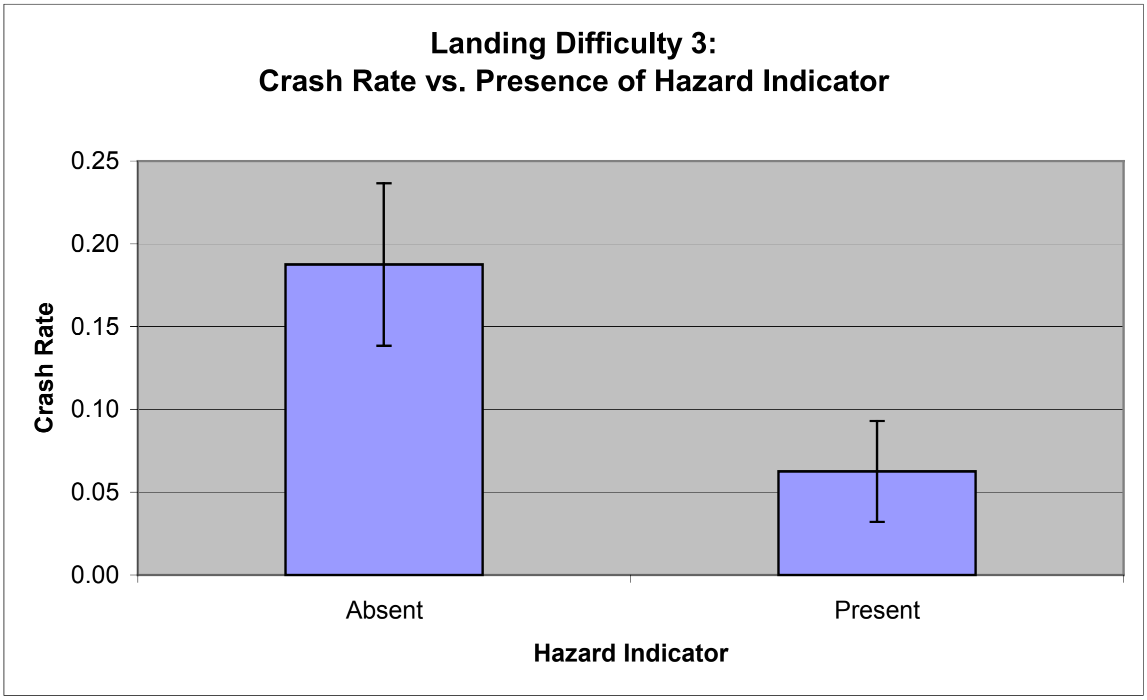
Table 7. Crash Statistics for All Landing Difficulties

Landing Difficulty	Hazard Indicator	Crashes	Total Approaches	Crash Rate	Standard Error
LD 1	No	6	64	0.0938	0.0367
LD 2	No	5	64	0.0781	0.0338
	Yellow	5	64	0.0781	0.0338
LD 3	No	12	64	0.188	0.0492
	Yellow	4	64	0.0625	0.0305
LD 4	No	15	64	0.234	0.0534
	Red	0	64	0	0

4.4.2.2 Hypothesis 1 confirmed

The mean crash rate at landing difficulty 3 when no hazard indicator was displayed was C_{NH} = 0.1875 (12 crashes in 64 runs), with a standard error of .0492. When a hazard indicator was displayed, the mean crash rate dropped to C_H = .0625 (4 out of 64) with a standard error of .0305 (Table 8). A t-test for paired samples shows that the hypothesis that the presence of the hazard indicator reduces the frequency of crashes during simulated shipboard helicopter landings is confirmed ($t=2.39$, $df=63$, $p=0.00985$). More formally, where H_0: $C_H = C_{NH}$ and H_1: $C_H < C_{NH}$ (both at LD=3), H_0 can be rejected with $p < 0.01$.

Table 8. Landing Difficulty 3 - Crash Data



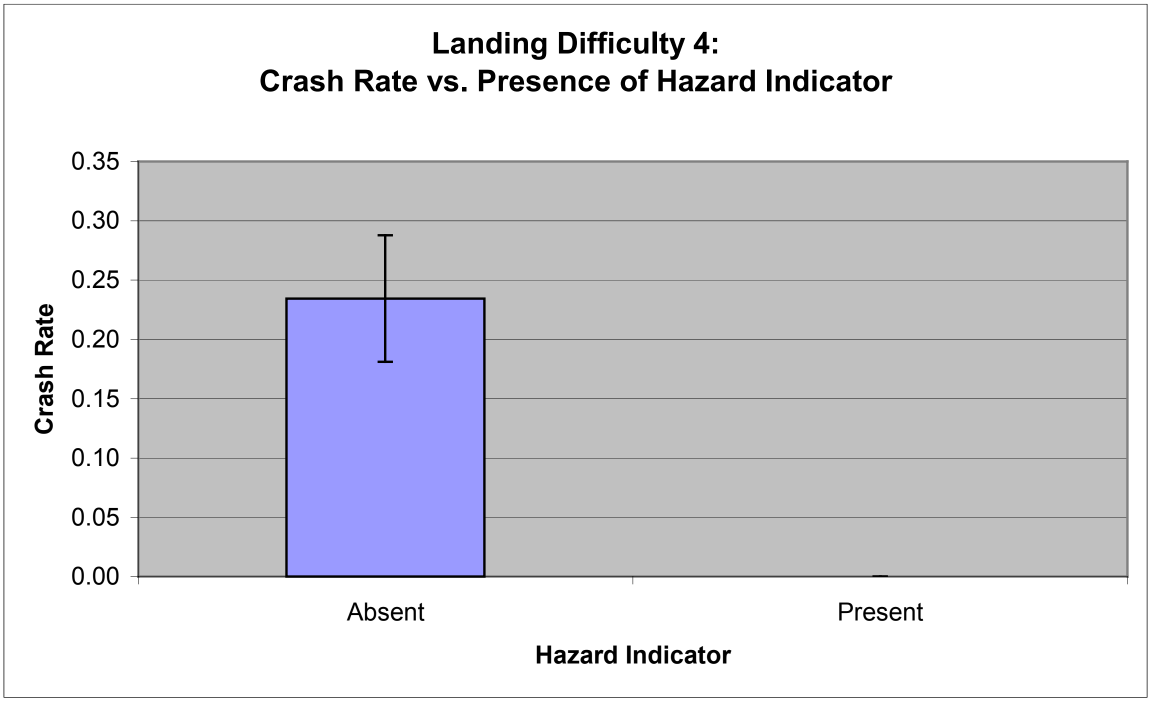
These strong results indicate the system should improve helicopter flight safety under hazardous conditions. During the tests, pilots remarked several times that the indicators were helpful warnings; that they were able to modify their flight path or power settings to counteract the known hazardous conditions, or make appropriate safety decisions based on knowledge gained from viewing the hazard indicators. Additionally, in the approaches without hazard indicators, pilots commented on several occasions that they were surprised by the wind conditions as they entered the hazardous areas. In a few of these runs where the pilot made such a comment, the approach terminated in a crash.

4.4.2.3 Hypothesis 2 confirmed

This test differs from the test for landing difficulty 3. With LD=4, a safe landing is not expected and it is not an object of the hazard indicator to facilitate landing. We did, however, wish to examine whether a hazard indicator designed for conditions that are merely difficult could continue to prevent accidents as conditions deteriorated below minimum landing criteria.

At landing difficulty 4 (beyond the capacity of the aircraft), there were 0 crashes in 64 approaches with the hazard indicator as opposed to 15 crashes out of 64 without the indicator, for crash rates of 0% and 23% respectively. A t-test for paired samples shows that this hypothesis—that the presence of the red hazard indicator combined with appropriate instructions to the pilot prevents crashes—is strongly confirmed ($t=4.39$, $df=63$, $p < 0.000022$). The mean crash rate for landing difficulty 4 with no indicator was $C_{NH} = 0.234$, and the standard error was .0534. When the indicator was present, mean crash rate C_H was 0 with standard error 0 (Table 9).

Table 9. Landing Difficulty 4 - Crash Data



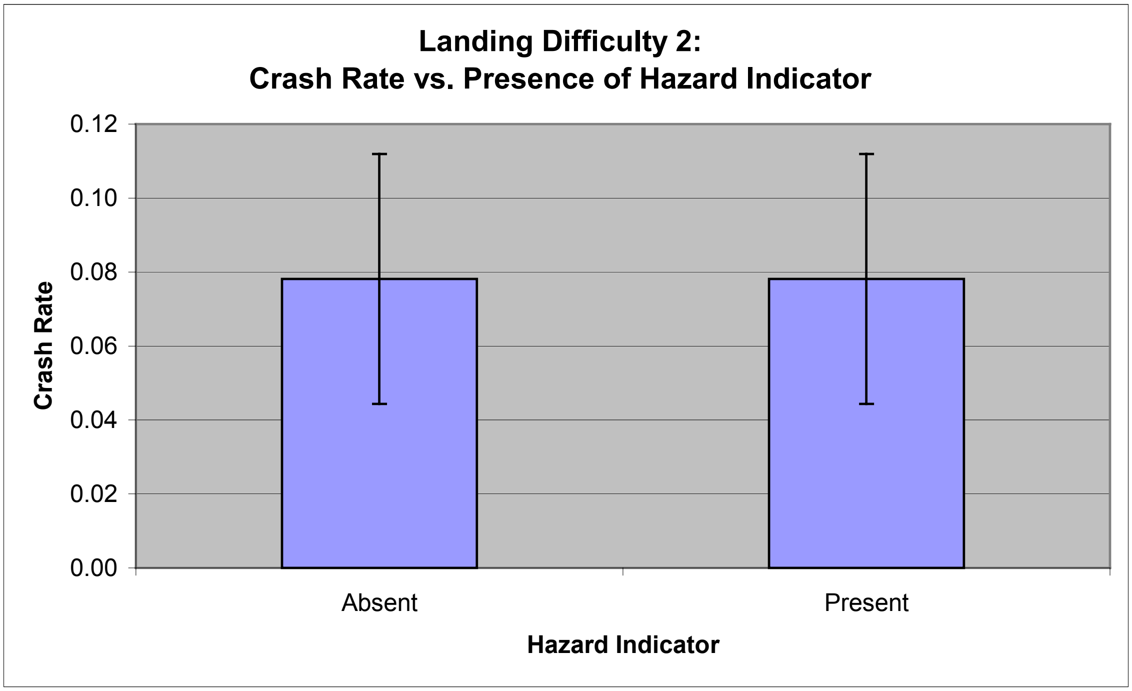
The result indicates that although pilots may sometimes continue into a situation that is beyond the capacity of the aircraft if they do not have sufficient knowledge of the danger of the situation, giving them the appropriate information in a clear and simple manner during the approach can prevent accidents. This is an improvement over the current envelope system because, as one pilot noted, the real-time display would be very helpful in case the winds shifted during the approach. Such shifts can occur after the pilot has consulted the relevant envelope and begun the approach and is no longer in a position to consult a manual. If the pilot suddenly saw a red hazard area appear on deck, the pilot would know immediately to "go around" or "wave off" (abort the approach).

For pilot 16, we experimented with not giving the pilot the standard operating procedure (SOP) of a mandatory go-around upon detection of the red indicator. This pilot continued each approach with a red hazard indicator until he got close to the red zone, then he aborted the approach. There was one exception: during one approach, he chose to land on the empty deck well aft of the hazardous zone over the designated landing spot. (In the simulator, there were no other aircraft on deck. In a real situation, it is likely that the deck would have been filled with aircraft, and he would have had to abort the approach.) In other words, he took almost the same actions as the other pilots, just a little later during the approach. Interestingly, during the post-flight debrief, this pilot stated that with the red hazard we should have given pilots a standard operating procedure of an automatic abort upon detection. Otherwise, he said, pilots might be tempted to go on and "test the waters." Although this variation with the last pilot could not produce any statistically valid results due to the small sample size, it suggested that that our results might have been similar had we not had an SOP for the red hazards for the first 15 pilots.

4.4.2.4 Hypothesis 3

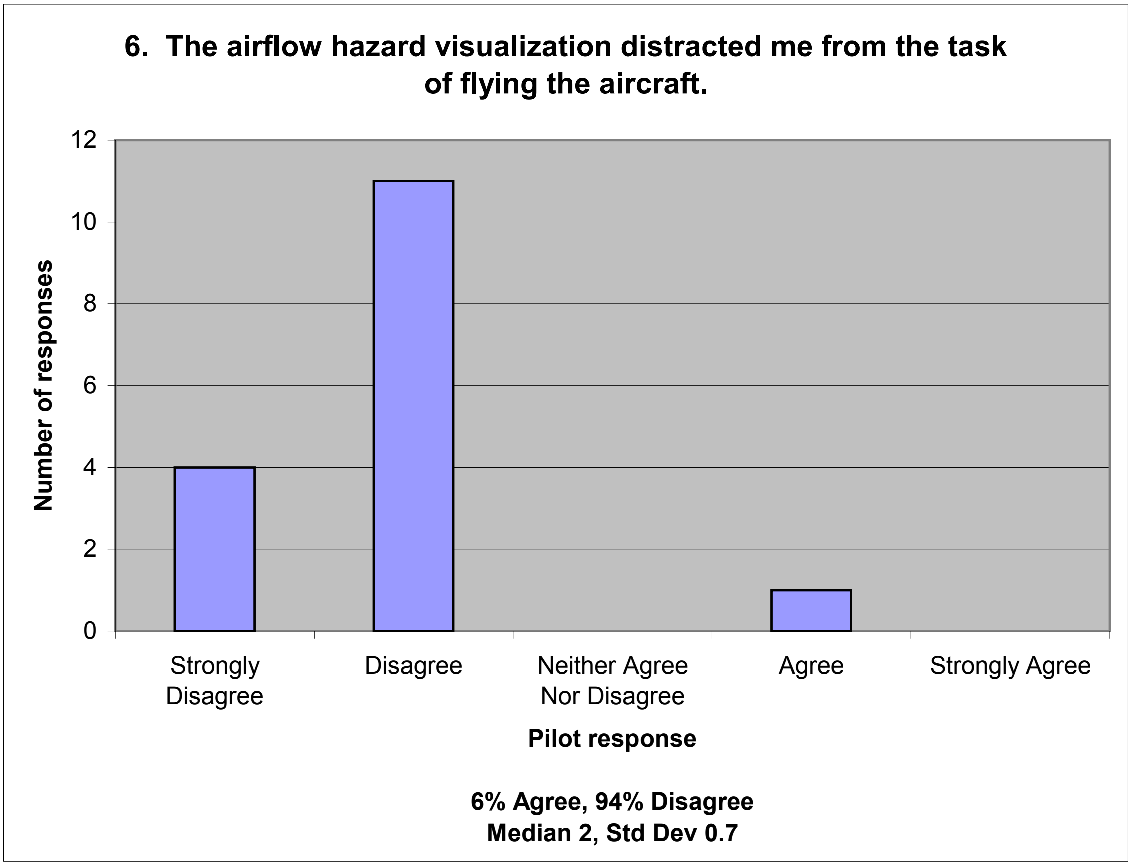
No negative effect of hazard indicator. It appears that the hazard indicators did not distract the pilots. The crash rate at LD 2 was the same with and without the indicator. Crash rate for both was identical, 7.8% or 5 crashes out of 64 for each set of approaches (Table 10). However, because the crash rate was low, with a sample of this size it is not possible to conclusively state that the hazard indicator made no difference in crash rate. (H_0: $C_{NH} = C_H$ and H_1: $C_{NH} \leq C_H$, both at LD=2; t=0, p=0.5).

Table 10. Landing Difficulty 2 - Crash Data



Among the pilots, however, there was excellent agreement that the hazard indicator was not distracting. (Based on interviews and the low-fidelity prototype study, we believe that "distraction" covers the great majority of negative qualities ascribed to a cockpit indicator by a pilot). On our simulation evaluation questionnaire, probe 6 was, "The airflow hazard visualization distracted me from the task of flying the aircraft." The pilots disagreed with this statement: 94% of the pilots answered "Strongly Disagree" (1) or "Disagree" (2) with the median "Disagree" (2) (Table 11).

Table 11. Probe 6 Results



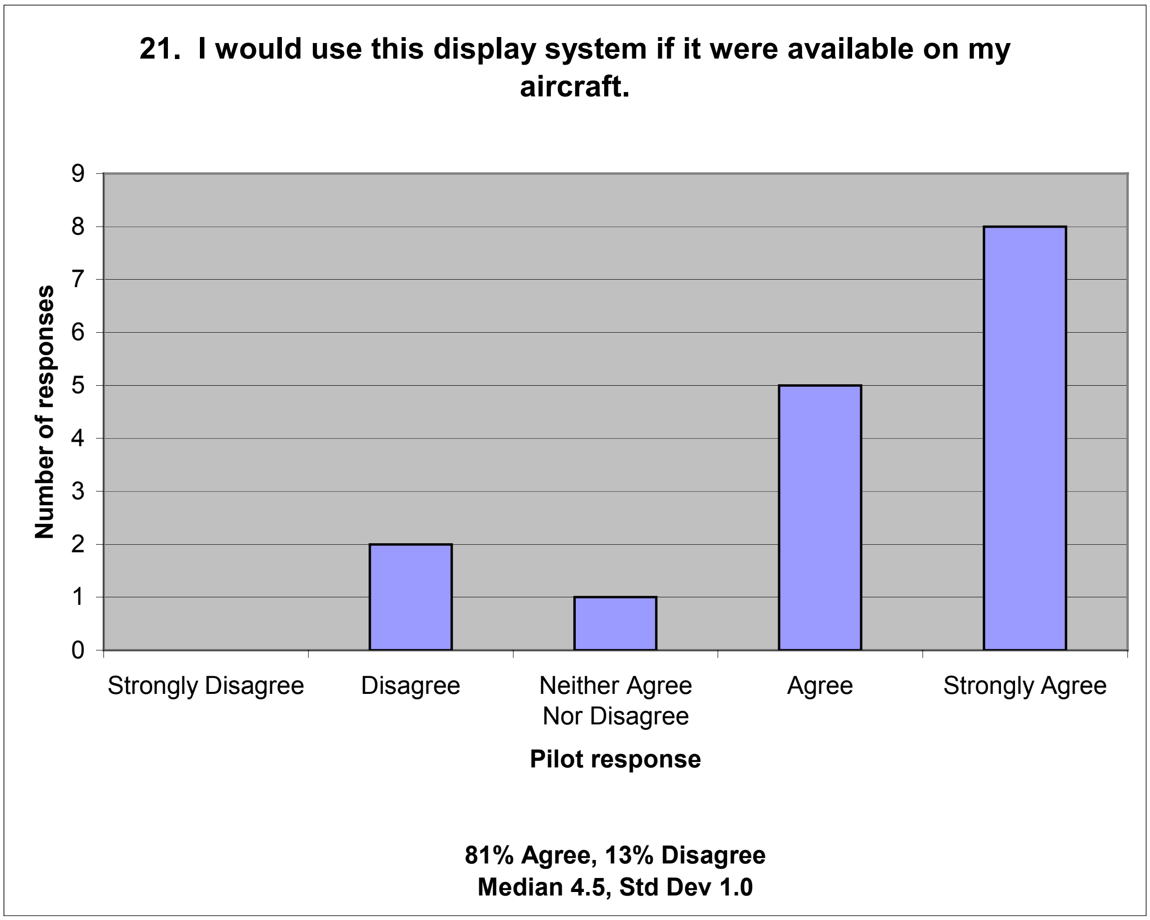
4.4.2.5 Hypothesis 4 confirmed

Pilot buy-in to new systems is extremely important as pilots have been known to ignore safety mechanisms if they feel they are "stupid" or intrusive, and override or turn off systems that they feel interfere with their handling of the aircraft [84].

However, although it was the first time the pilots were flying the simulator and the first time they had seen a visual hazard warning system, they were quite enthusiastic about the system. When pilots were asked to report their level of agreement with the statement, "I would use this system if it were available on my aircraft," eight pilots chose

"Strongly Agree" (5), five chose "Agree" (4), one chose "Neither Agree Nor Disagree" (3) and two chose "Disagree" (2). Median response was 4.5, between "Strongly Agree" and "Agree." (Table 12) This indicates confirmation of Hypothesis 4, that pilots would use the system.

Table 12. Probe 21 Results



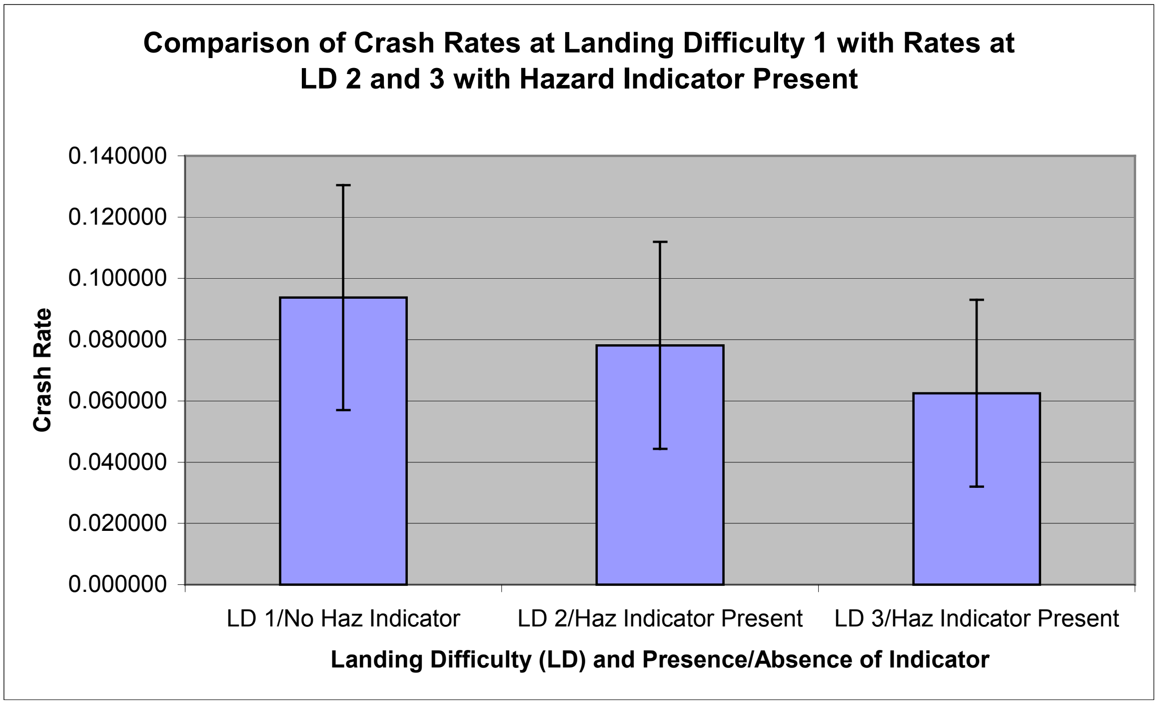
Several of the pilots wanted to know how far the system was from implementation in aircraft. Even considering the three pilots who did not agree with wanting to use the system, two of those gave nuanced responses; one said he needed more time with the system before he could make a decision, while another pilot favored its use for less experienced pilots but felt he already knew where all the shipboard hazards were. Only one felt his HUD was already too visually cluttered and he did not want anything else displayed on it; he preferred an auditory warning. (HUDs have selectable display modes so pilots can choose the amount of information displayed—these modes are called "clutter modes.") Given how resistant pilots can be to externally imposed changes, that 13 out of 16 pilots, or 81%, say they would use the system after having spent one hour with it is a very strong positive result.

4.4.2.6 Control group (LD 1)

Because conditions in the simulator are somewhat different than in a real helicopter, and visual and proprioceptic feedback is reduced (no chin bubble through which helicopter pilots can look down past their feet and see how close they are to the deck, no depth perception in the visuals, no bump when the landing gear contacts the deck, etc.), and especially because pilots are flying it for the first time without any training with an instructor (the usual procedure when transitioning to a new aircraft), a certain number of crashes in the simulator are to be expected. For this reason we included a set of low-hazard approaches in the study to serve as a control (LD 1).

The crash rate at landing difficulty 1 was 9.4% (6 out of 64), which is not significantly different from LD 2 or LD 3's crash rates (5 out of 64 and 4 out of 64, respectively; t-test, $p=0.38$ and $p=0.26$) when the hazard indicator is present (Table 13).

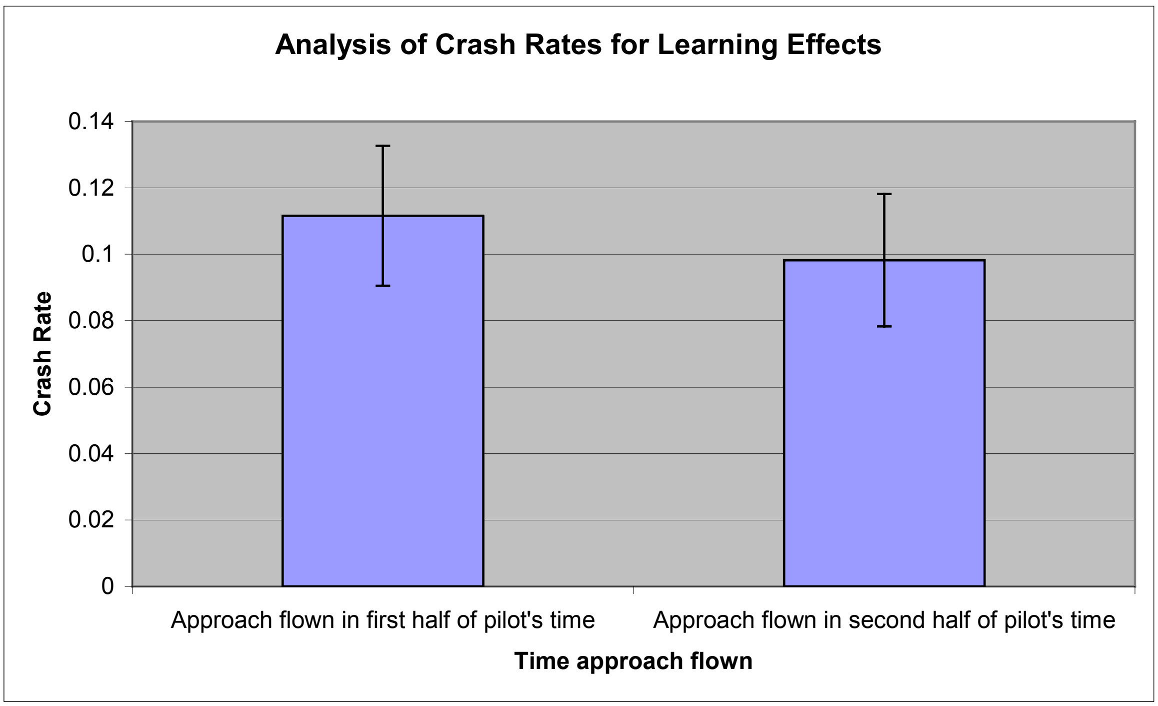
Table 13. No significant difference between crash rates at LD 1 (control) and LD 2 with hazard indicator and LD 3 with hazard indicator



4.4.2.7 Learning effects

For the first half of the simulator test, the pilots crashed 25 times out of 224 approaches flown for a crash rate of 11.2%, while in the second half of their tests, the pilots crashed 22 times out of 224 approaches, for a crash rate of 9.8% (Table 14).

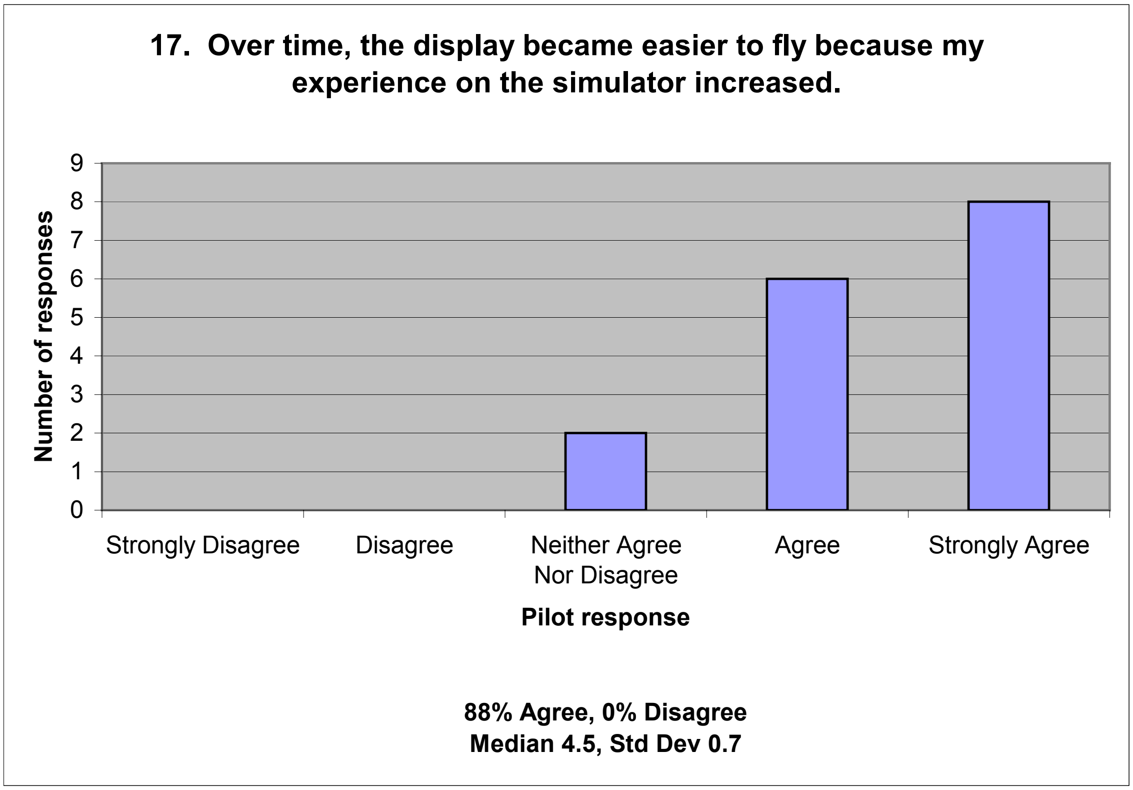
Table 14. No apparent learning effects in study



This is not a significant difference (t-test, t=0.46, df=445, p=0.32), although the pilots did state that they believed they performed better as they flew the simulator longer. (Probe 17: "It became easier over time to fly because my experience on the simulator increased." Eight pilots answered "Strongly Agree" (5), six pilots chose "Agree" (4), and two pilots chose "Neither Agree or Disagree" (3). Median response was 4.5. (Table 15))

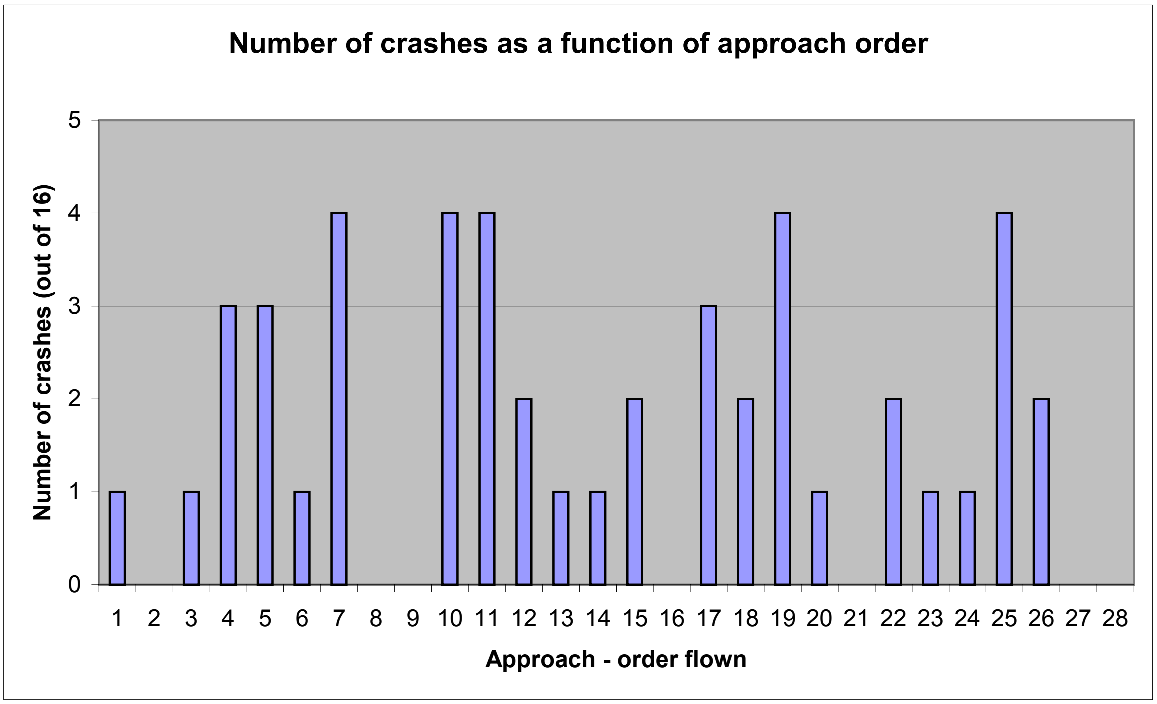
This appears to indicate that learning effects did not bias our study, as was intended in its construction.

Table 15. Probe 17 Results



We considered whether there could be other reasons for this result. For example, a few of the pilots commented toward the end of the 28 approaches that they were getting tired. It is possible that there were more crashes at the beginning of the flights, but this effect was masked by more crashes at the very end of each pilot's simulator time. In order to test this theory, we graphed crashes as a function of approach order (Table 16). In this graph, the x-axis lists the order flown, from 1 to 28, and the y-axis the number of crashes at that point (out of 16 approaches flown). The graph makes evident that there is no such pattern of bias in the number of crashes as a function of approach order. Therefore, we concluded that learning effects did not bias our study.

Table 16. No evidence for learning effects or other global effects as a function of order flown



4.4.3 Ancillary Results

4.4.3.1 Go-Around Rate Analysis

We also analyzed the overall rates of go-arounds. A go-around is an aborted landing, or “waveoff,” where the pilot decides a safe landing is not probable, and proceeds to climb to re-enter the pattern and (possibly) attempt the landing again. In our experiment, as soon as the pilot called for an aborted landing, we terminated the run, and the pilot did not attempt another landing under those conditions.

In reality, were a pilot to go around, the next step would most likely be another landing approach, perhaps calling for the ship to turn further into the wind, or perhaps requesting a different landing spot. However, for the purposes of our simulation, we counted go-arounds separately from completed landings. Each approach, therefore, took one of three possible terminations: a completed landing, a go-around (“waveoff”), or a crash. Because go-arounds are a frequent and necessary part of safe flying, for our main analysis above we considered the crash rate as our primary dependent variable in determining whether or not our system had a positive effect on flight safety under the stated conditions.

As a (fixed-wing) flight instructor myself, I teach my students that all landing approaches should really be considered approaches to go around. Any number of go-arounds are better than making a destabilized approach to landing that could end in a crash. Because this attitude is common in the aviation community, an increased number of go-arounds would not be considered a negative result. However, it can be supposed that there are operational considerations in naval aviation whereby a go-around is costly in some sense (although it preserves the aircraft and pilot). Therefore, a hazard indication system that does not increase go-arounds would be (other factors equal) preferable to one that does.

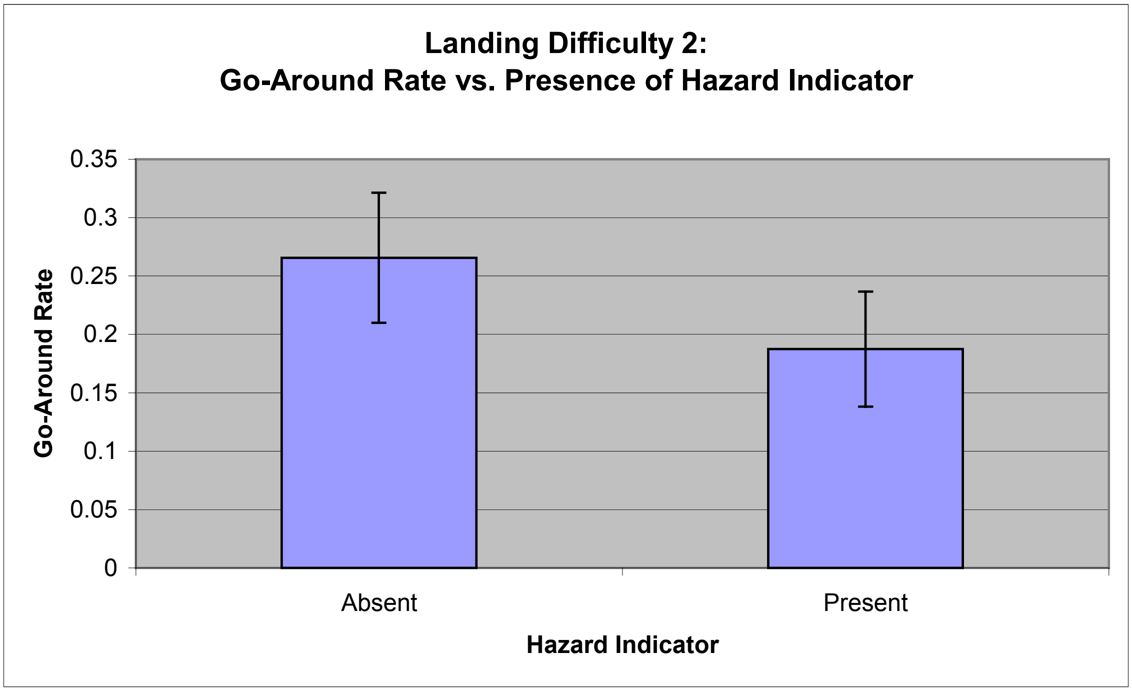
Go-around data is summarized below (Table 17):

Table 17. Go-Around Statistics for All Landing Difficulties

Landing Difficulty	Hazard Indicator	Go-Arounds	Total Approaches	Go-Around Rate	Standard Error
LD 1	No	3	64	0.0469	0.0266
LD 2	No	17	64	0.266	0.0556
	Yellow	12	64	0.188	0.0492
LD 3	No	22	64	0.344	0.0598
	Yellow	23	64	0.359	0.0605

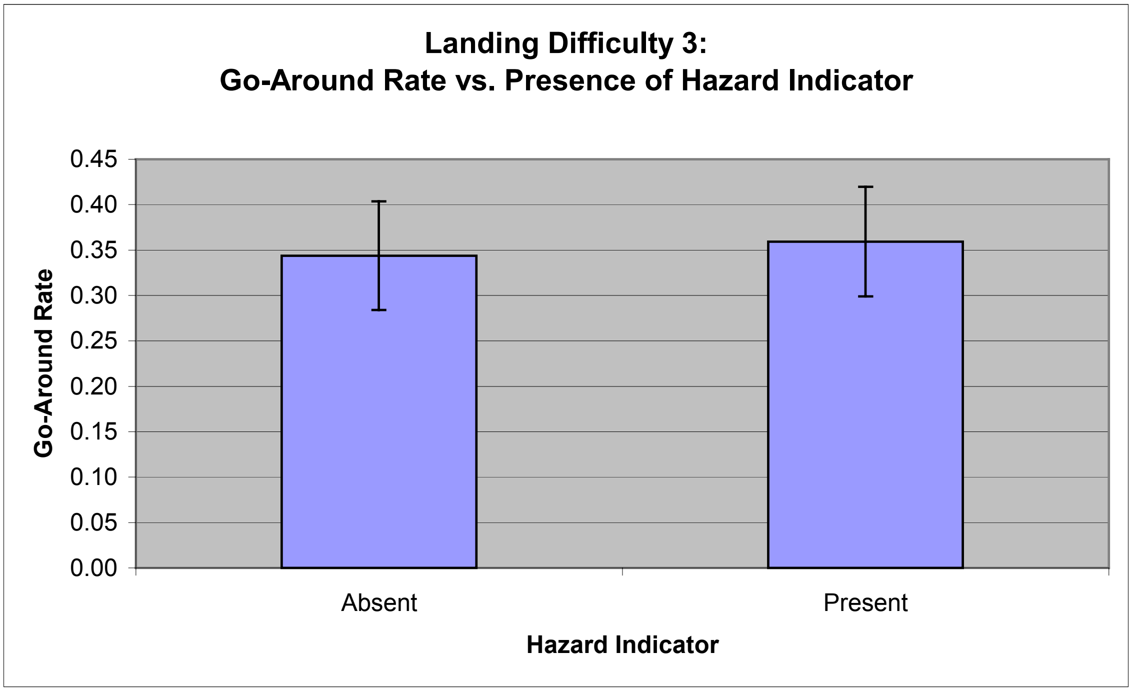
The go-around rate at landing difficulty 2 with no hazard indicator was 17 out of 64 approaches (a rate of 0.266 with a standard error of 0.0556) and 12 out of 64 (a rate of 0.188 with a standard error of 0.0492) with the hazard indicator present (Table 18). This is not a significant difference (t=1.04, df=63, p=0.15) for landing difficulty 2.

Table 18. Landing Difficulty 2 - Go-Around Data



At landing difficulty 3, the go-around rate when the hazard indicator was absent was 22 out of 64 (a rate of 0.344 with a standard error of 0.0598), almost identical to the rate when the hazard indicator was visible, 23 out of 64 (a rate of 0.359 with a standard error of 0.0604), again, not a significant difference ($t=0.18$, $df=63$, $p=0.427$) (Table 19).

Table 19. Landing Difficulty 3 - Go-Around Data



As discussed in Section 5.13.1, for cases where ANOVA is applicable it is a more conservative test of significance than individual t-tests. For the go-around data, a two-way ANOVA on landing difficulty (2, 3) and hazard indicator (present, absent) shows neither a significant difference due to either factor alone, nor a significant interaction between the factors (Fcrit = 6.7; for landing difficulty F = 4.9, p=0.028; for hazard F= 0.31, p=0.58; for the interaction F=0.69, p=0.41).

We did not analyze the data for landing difficulty 4 because we instructed fifteen of the sixteen subjects to make go-arounds whenever they detected a red hazard indicator in their path, so any results from landing difficulty 4 would be artificial.

It appears, therefore, that the presence or absence of the hazard indicator at landing difficulties 2 and 3 does not affect the go-around rate. Thus, analyzing the go-around data does not lead to any changes in our conclusions about the four hypotheses described above.

4.4.3.2 Landing Rate Analysis

In our study, whenever a pilot chose to make a go-around, the number of completed landings was reduced by one. So the analysis of completed landings in isolation has limited usefulness. Nevertheless, we include it here for completeness.

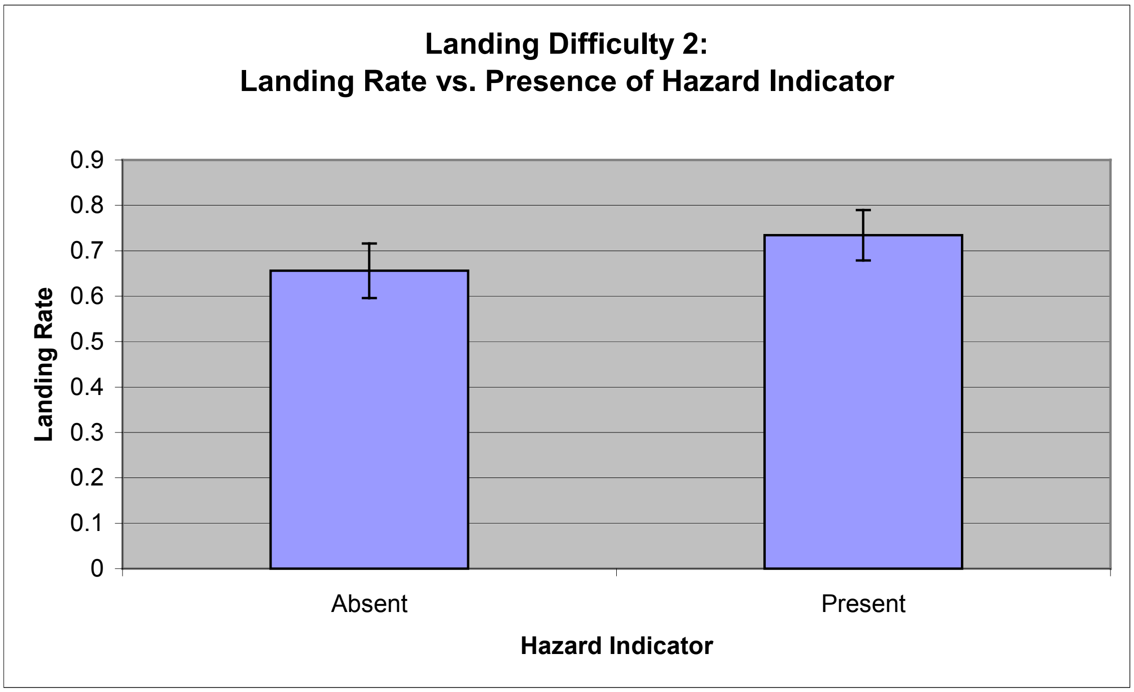
(Table 20) summarizes the data for completed landings at landing difficulty levels 1, 2, and 3.

Table 20. Landing Statistics for All Landing Difficulties

Landing Difficulty	Hazard Indicator	Landings	Total Approaches	Landing Rate	Standard Error
LD 1	No	55	64	0.859	0.0438
LD 2	No	42	64	0.656	0.0598
	Yellow	47	64	0.734	0.0556
LD 3	No	30	64	0.469	0.0629
	Yellow	37	64	0.578	0.0622

The number of completed landings does increase with the presence of the hazard indicator at both landing difficulties 2 and 3. At landing difficulty 2, the landing rate increases from 42 out of 64 (landing rate 0.656, standard error 0.0598) with no hazard indicator to 47 out of 64 (landing rate 0.734, standard error 0.0556) with the hazard indicator (Table 21). However, a t-test for paired samples shows this is not a significant difference (t=0.96, df=63, p=0.17).

Table 21. Landing Difficulty 2 - Landing Data



At landing difficulty 3, the landing rate increases from 30 out of 64 (landing rate 0.469, standard error 0.0629) with no hazard indicator to 37 out of 64 (landing rate 0.578, standard error 0.0622) with the hazard indicator present. This is also not a significant difference as shown by a t-test for paired samples (t=1.36, df=63, p=0.09).

However, as we explained above, because we terminated the approach when the pilot called for a go-around, the analysis of the landing rate is not as powerful an indicator of the benefit of our system as the analysis of the crash rate. In the real world, we believe that most of the go-arounds would have eventually resulted in a safe landing, and thus the true rate of safe landings is best measured by the number of go-arounds plus the number of completed landings in our study, or the total number of approaches minus the crash rate. In our study, the number of approaches was fixed and the crash rate was the primary object of study.

4.4.3.3 Analysis by Pilot Experience Level

An interesting question was whether pilot experience level had any effect on performance, and on the effectiveness of the hazard indicators. In order to look at this question, we divided the 16 pilots into three groups, where there were natural gaps in their experience levels: less experienced, moderately experienced, and highly experienced (Table 22).

Table 22. Pilots grouped by experience level

Pilot Experience Level	Helicopter Flight Hours	Number of Pilots in Group
Less experienced	200 – 850	5
Moderately experienced	1500 – 3200	7
Highly experienced	4000 - 7300	4

One of the very experienced pilots had commented that he did not learn anything new from the placement of the hazard indicators, but he felt it might be a good training aid for more inexperienced pilots. Additionally, most of the less experienced pilots stated that they did learn something from the hazard indicators. (See probe 19 on learning.)

We therefore examined the data for evidence that the decrease in crash rates was concentrated among the pilots with less experience. The reduction, however, was seen across all experience levels, although we could not obtain statistical significance in most cases due to the lower sample numbers. The data is summarized below.

4.4.3.3.1 Less experienced pilots

There were five pilots with helicopter flight hours from 200 to 850. This group flew a total of 140 approaches at all landing difficulty levels. Crash rates for all difficulty levels for this group of pilots are summarized in (Table 23).

Table 23. Crash statistics for less experienced pilots (group of 4)

Landing Difficulty	Hazard Indicator	Crashes	Total Approaches	Crash Rate	Standard Error
LD 1	No	1	20	0.05	0.05
LD 2	No	0	20	0.0	0.0
	Yellow	1	20	0.05	0.05
LD 3	No	4	20	0.20	0.092
	Yellow	1	20	0.05	0.05
LD 4	No	4	20	0.20	0.092
	Red	0	20	0.0	0.0

For this group, the reduction in crash rate at landing difficulty 3 from 4 out of 20 (crash rate 0.20, standard error 0.092) without the hazard indicator to 1 out of 20 (crash rate 0.05, standard error 0.05) with the hazard indicator is significant. A t-test for paired samples yields ($t=1.83$, $df=19$, $p<0.041$). There is no significant difference at landing difficulty 2. At landing difficulty 4, the difference in crash rate is significant as shown by a t-test for paired samples ($t=2.18$, $df=19$, $p<0.021$). So our hypotheses 1, 2 and 3 hold for this group of less experienced pilots.

4.4.3.3.2 Moderately experienced pilots

The group of seven moderately experienced pilots had helicopter flight hours from 1500 to 3200. Their overall crash rate (13%) was slightly higher than the overall crash rates for both the less experienced (8%) and the highly experienced pilots (8%), but this difference was not significant. The crash statistics for the moderately experienced pilots are given in (Table 24).

Table 24. Crash statistics for moderately experienced pilots (group of 7)

Landing Difficulty	Hazard Indicator	Crashes	Total Approaches	Crash Rate	Standard Error
LD 1	No	4	28	0.143	0.067
LD 2	No	4	28	0.143	0.067
	Yellow	3	28	0.107	0.060
LD 3	No	6	28	0.212	0.079
	Yellow	3	28	0.107	0.060
LD 4	No	7	28	0.25	0.084
	Red	0	28	0.0	0.0

We see the same trends at all landing difficulties that we saw in the full group as well as the less experienced group: about the same number of crashes at landing difficulty 2 both without (4 out of 28 for a crash rate of 0.143, standard error of 0.067) and with the hazard indicator (3 out of 28 for a crash rate of 0.107, standard error of 0.060), and at landing difficulty 3, more crashes without (6 out of 28 for a crash rate of 0.214, standard error of 0.079) versus with the hazard indicator (3 out of 28 for a crash rate of 0.107, standard error 0.060). However, neither of these differences achieves significance with this small (7 pilots) group.

The crash rate difference at landing difficulty 4 is significant, as shown by a t-test for paired samples ($t=3.0$, $df=27$, $p<0.0029$).

So the group of moderately experienced pilots does not appear to differ from the overall group, nor from the group of less experienced pilots.

4.4.3.3.3 Highly experienced pilots

We categorized four pilots from our subject population as highly experienced. These pilots had from 4000 – 7300 helicopter flight hours. Their crash rates also followed the general trend, as seen in (Table 25).

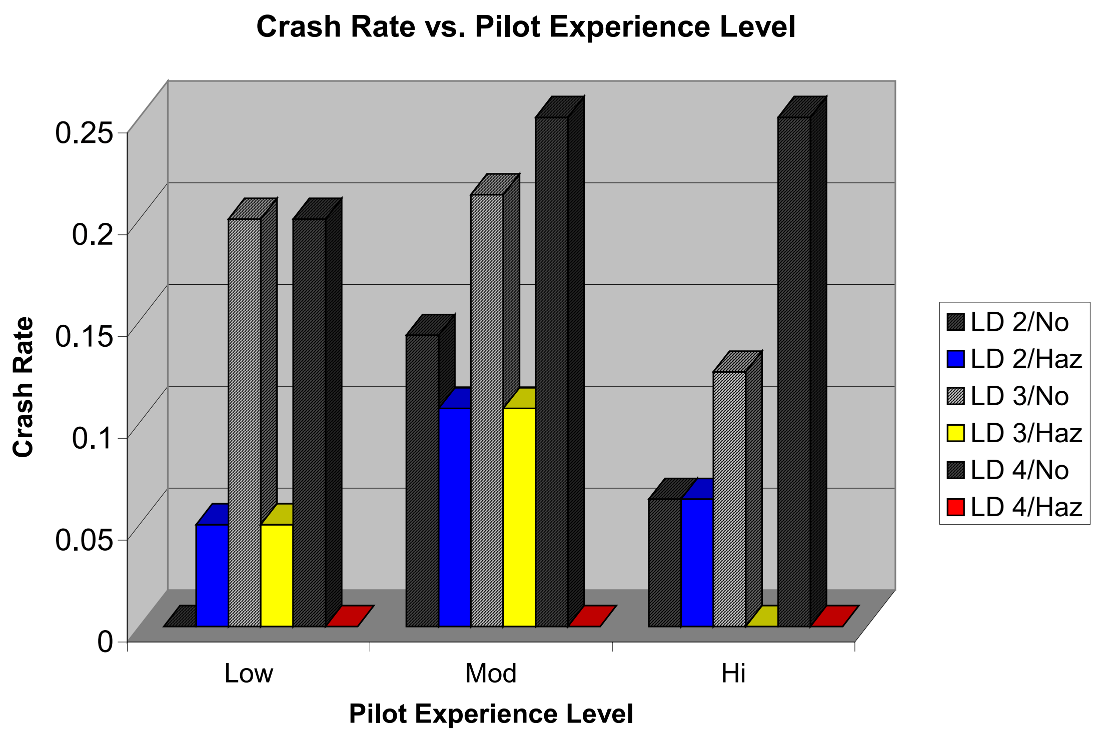
Table 25. Crash statistics for highly experienced pilots (group of 4)

Landing Difficulty	Hazard Indicator	Crashes	Total Approaches	Crash Rate	Standard Error
LD 1	No	1	16	0.0625	0.0625
LD 2	No	1	16	0.0625	0.0625
	Yellow	1	16	0.0625	0.0625
LD 3	No	2	16	0.125	0.085
	Yellow	0	16	0.0	0.0
LD 4	No	4	16	0.25	0.11
	Red	0	16	0.0	0.0

Because the sample size is so small, the difference in crash rates at landing difficulty 3, 2 out of 16 without the hazard display (crash rate 0.125, standard error 0.085) versus 0 out of 16 with the hazard indicator (crash rate 0, standard error 0) was not significant (t-test, paired samples, $t=1.46$, $df=15$, $p=0.082$). However, at landing difficulty 4, significance was reached in the difference between 4 crashes out of 16 approaches without the hazard indicator versus no crashes with the display (t-test, paired samples, $t=2.24$, $df=15$, $p<0.02$).

In other words, the trends suggest that our hypotheses 1, 2 and 3 are true for the group of highly experienced pilots as well, despite the one pilot's remark that he did not need the hazard indicators because he already knew where all the regions of hazardous airflow were located on shipboard. The following graph summarizes all the data (Table 26).

Table 26. No significant difference between pilot groups based on experience level



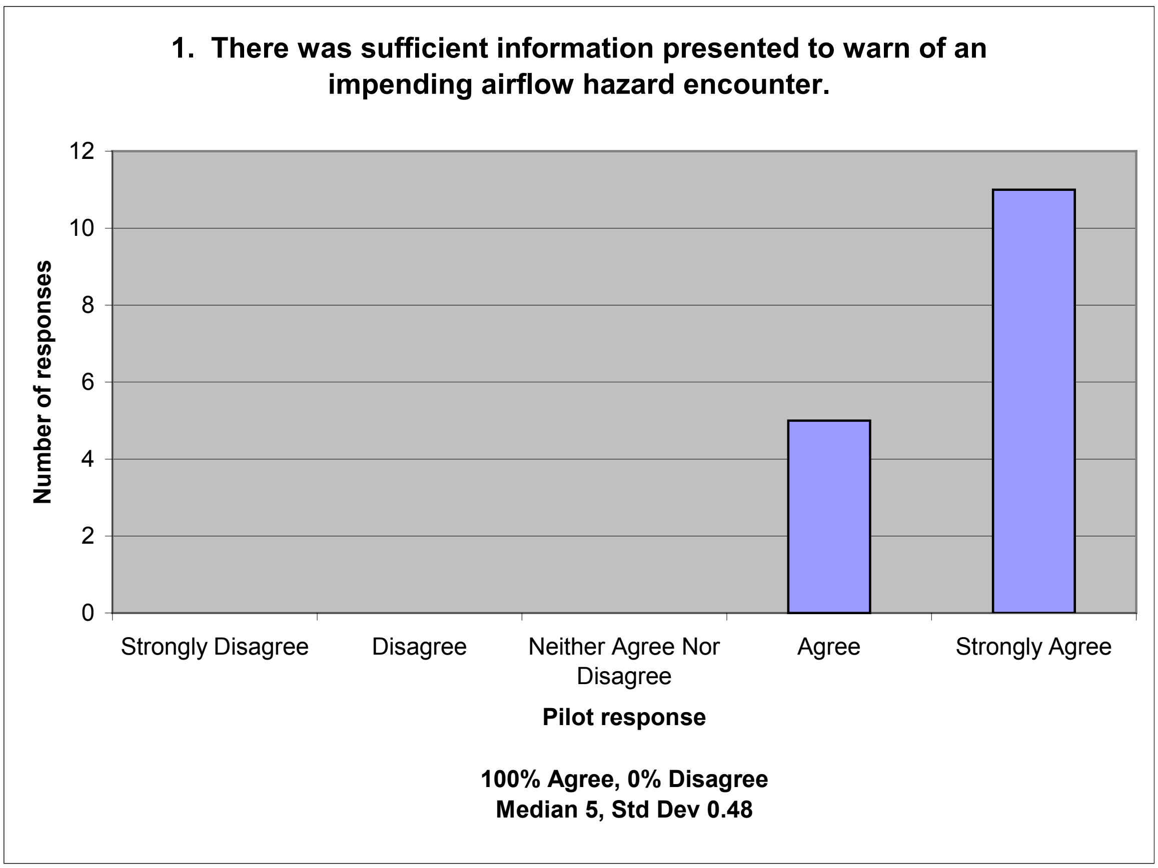
4.4.3.4 Analysis of Subjective Data from Pilot Evaluations

All pilots filled out a 21-probe Likert-scale post-simulation evaluation. The possible responses were (1) Strongly Disagree, (2) Disagree, (3) Neither Agree Nor Disagree, (4) Agree, or (5) Strongly Agree. In this section, we present the results of the probes other than those previously discussed in this chapter.

4.4.3.4.1 Probe 1. There was sufficient information presented to warn of an impending airflow hazard encounter.

All pilots agreed that the chosen hazard indicator symbols provided adequate warning of hazardous airflow in the flight path (Table 27).

Table 27. Probe 1 Results

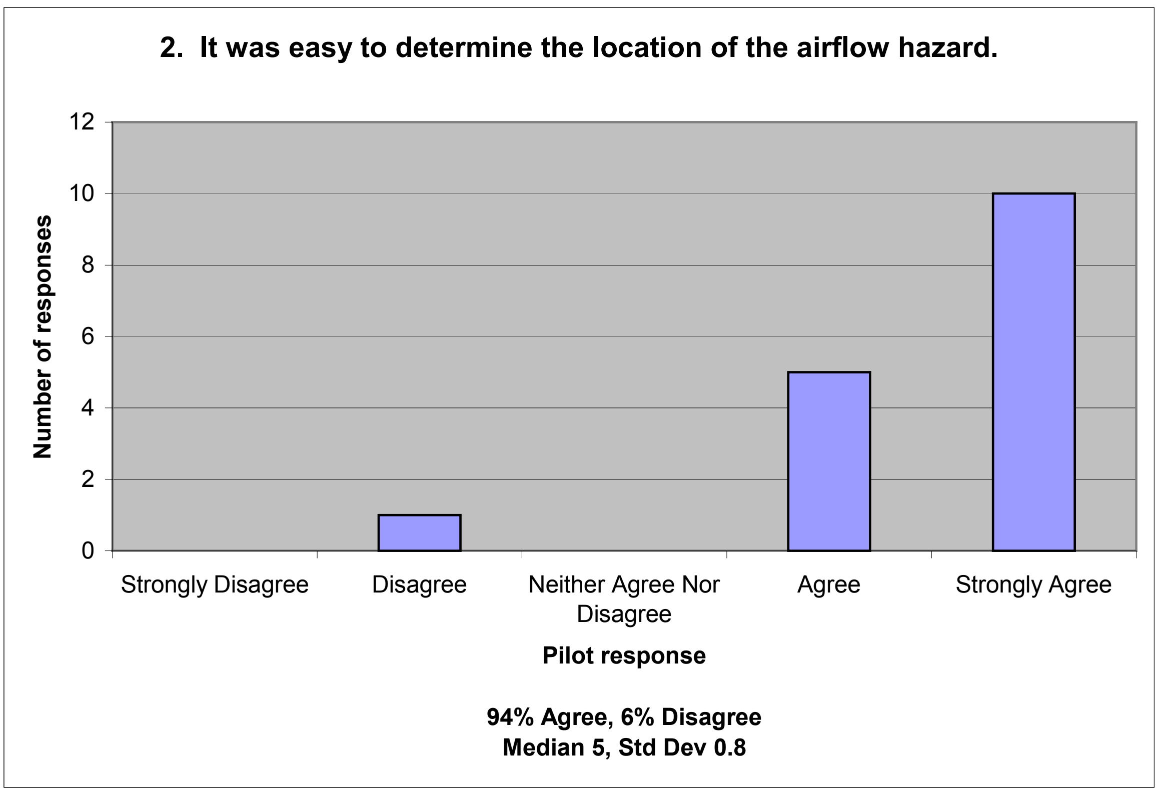


Verbal commentary by the pilots concurred with this response. The pilots had no trouble detecting the hazard indicators, even though they were somewhat grayed out on the projection screens of the simulator.

4.4.3.4.2 Probe 2. It was easy to determine the location of the airflow hazard.

(Table 28) demonstrates that pilots agreed that it was easy to detect the three-dimensional location of the hazardous area. One pilot commented that knowing the exact location of the airflow hazard "made decision making easy," and that they liked knowing exactly where the turbulence was located and "not guessing."

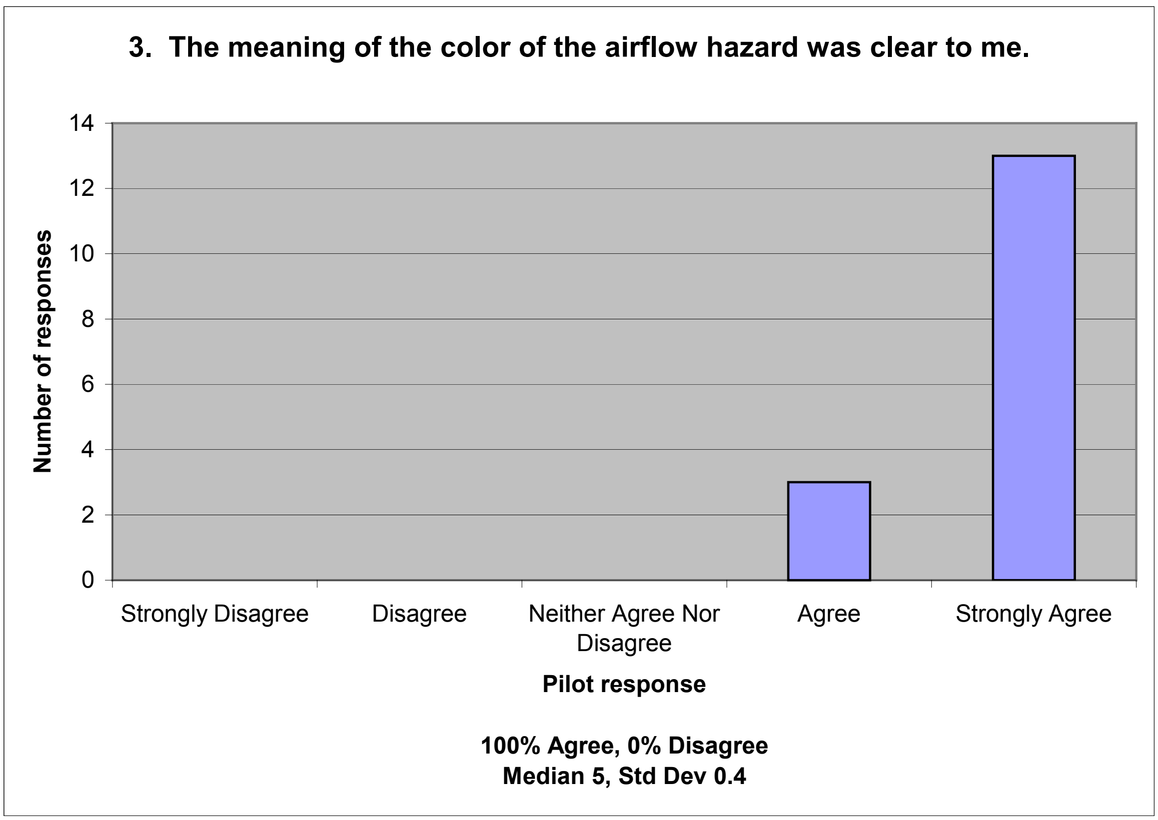
Table 28. Probe 2 Results



4.4.3.4.3 Probe 3. The meaning of the color of the airflow hazard was clear to me.

As we learned from the low-fidelity prototype, the mapping of the color red to danger and the color yellow to caution is universal in the aviation community. (Table 29) shows the pilots' strong agreement on this subject.

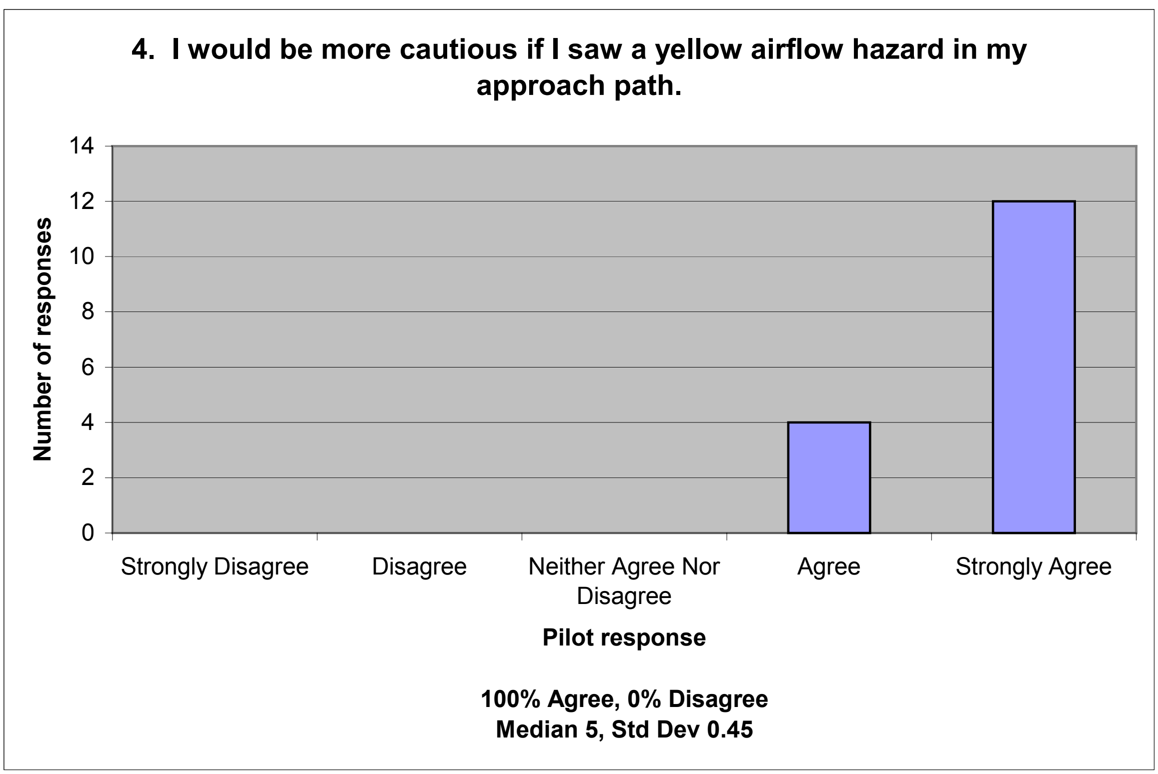
Table 29. Probe 3 Results



4.4.3.4.4 Probe 4. I would be more cautious if I saw a yellow airflow hazard in my approach path.

As (Table 30) illustrates, pilots exhibited caution upon viewing yellow hazard indicators. Several pilots commented that they changed their flight paths based on the location of the hazard indicators. We conjecture that this pilot action contributed to the lower crash rates at landing difficulty 3 when the yellow hazard indicators were present. One pilot did warn of the possibility that the hazard indicator could make pilots overcautious; however, the go-around data did not seem to bear this out (there was no increase in go-arounds with the presence of a yellow hazard indicator).

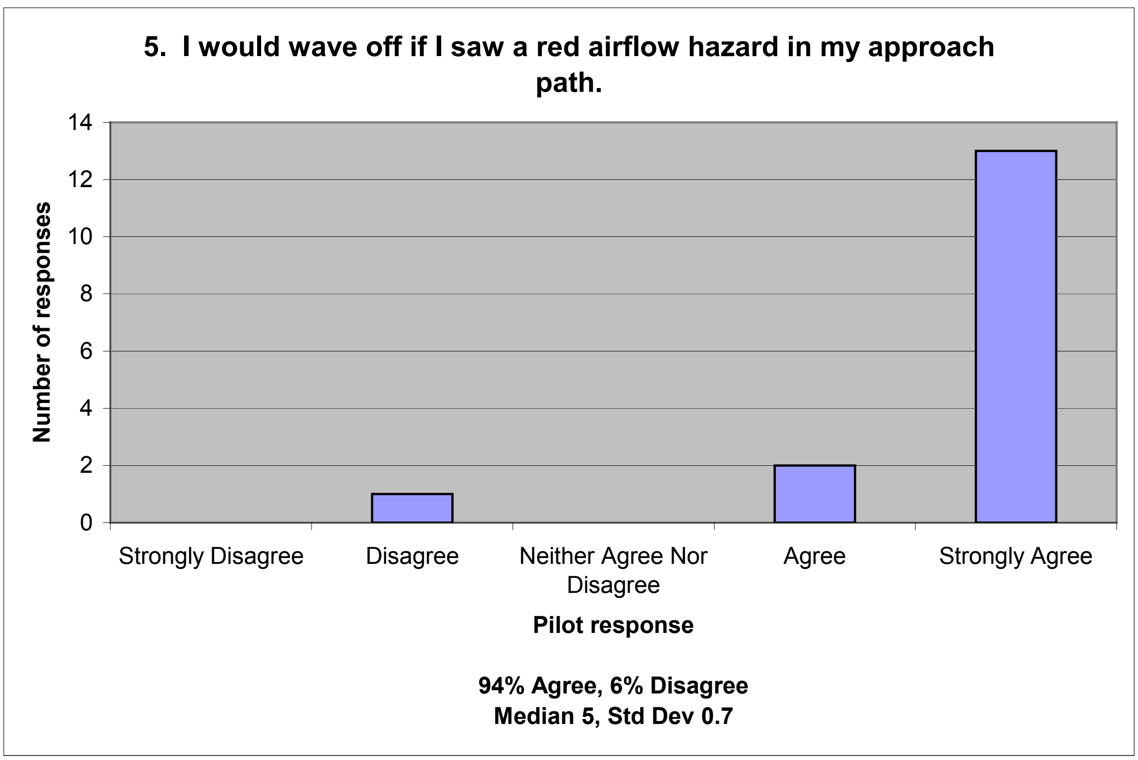
Table 30. Probe 4 Results



4.4.3.4.5 Probe 5. I would wave off if I saw a red airflow hazard in my approach path.

We instructed fifteen of the sixteen pilots to make a go-around or wave off as soon as they detected a red airflow hazard, so all of them agreed as shown in (Table 31). The sixteenth pilot, to whom we did not provide this instruction, was the only one to disagree. However, he did comment after the simulation that in his judgment we *should* have provided a standard procedure of going around or waving off when the hazard was red.

Table 31. Probe 5 Results



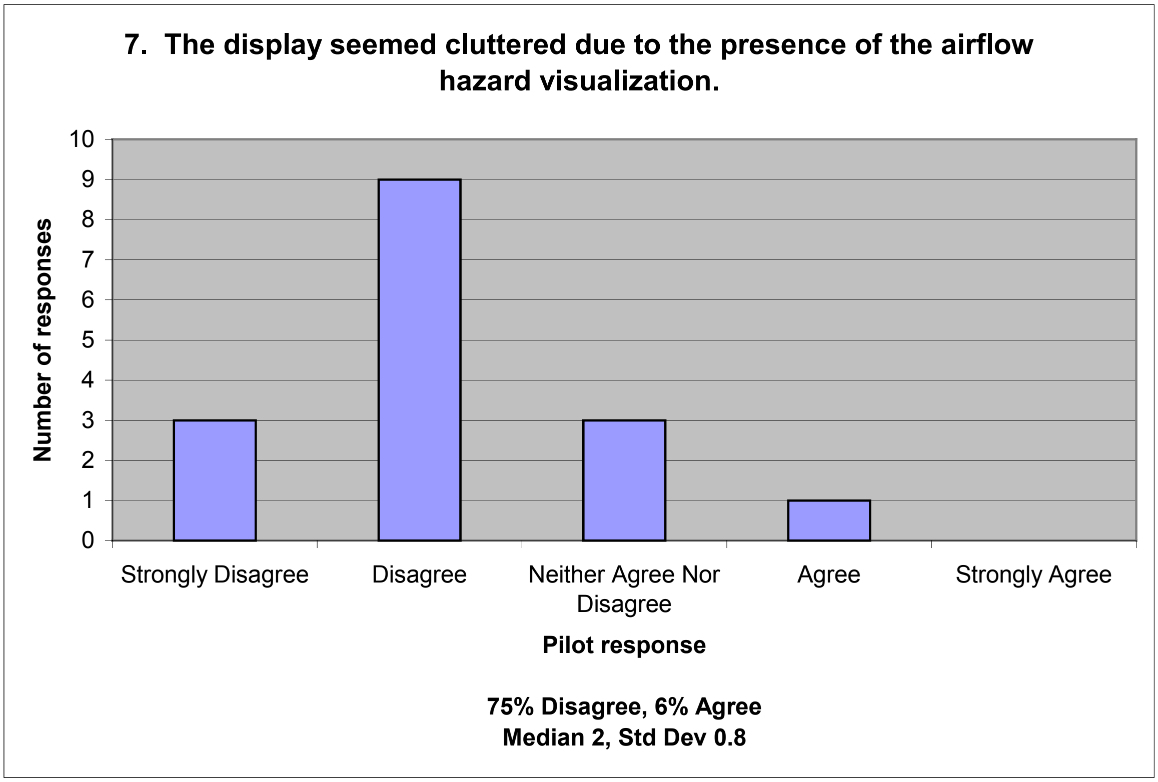
4.4.3.4.6 Probe 6. The airflow hazard visualization distracted me from the task of flying the aircraft.

This was discussed earlier, in (Table 11) in the context of measuring negative performance effects of the hazard indicator. The pilots almost universally concurred that the hazard indicators were not distracting, and this was borne out by their performance.

4.4.3.4.7 Probe 7. The display seemed cluttered due to the presence of the airflow hazard visualization.

Most of the pilots did not find that the presence of the scene-linked visual aids cluttered the display (Table 32). The single pilot who agreed with the probe did not provide a reason or otherwise elaborate on his response. One pilot commented that he liked the hazard indicator appearing to be part of the three-dimensional outside scene, because he found that sometimes there was "just too much symbology" on the HUD; that is, he judged the scene-linked display to reduce the appearance of clutter relative to existing HUD indicators.

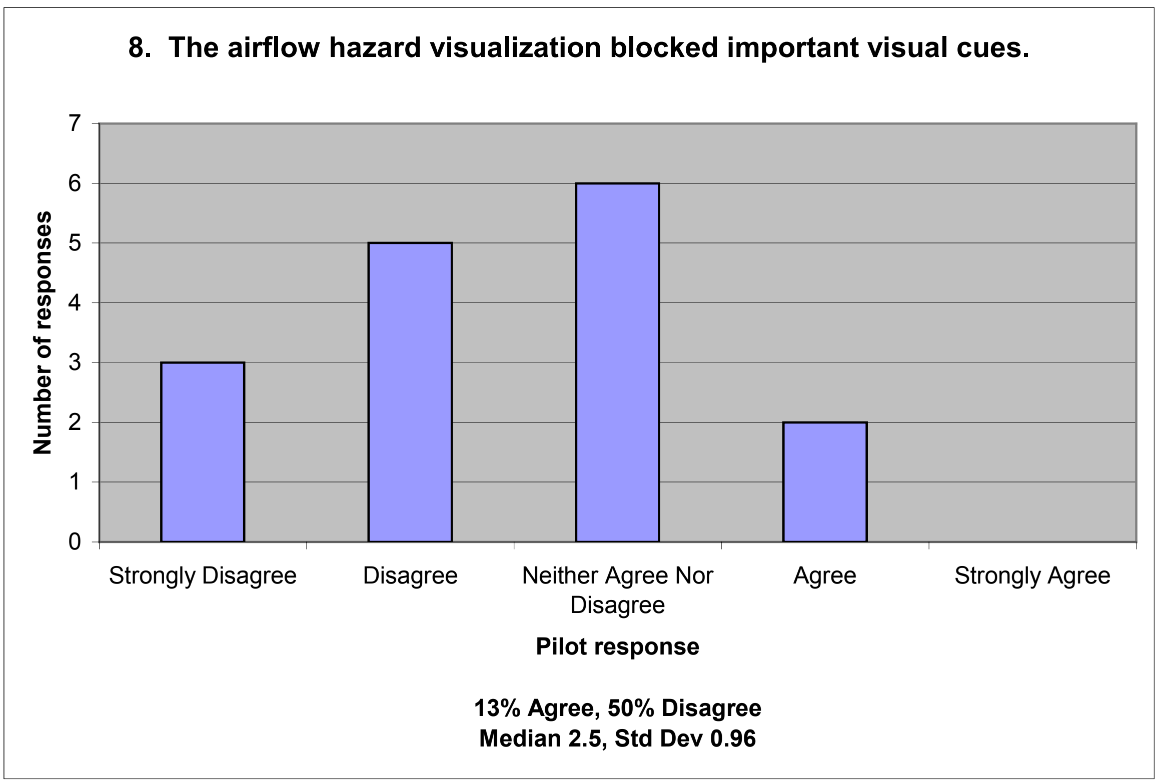
Table 32. Probe 7 Results



4.4.3.4.8 Probe 8. The airflow hazard visualization blocked important visual cues.

Overall, the pilots tended to disagree with this statement (Table 33). One pilot commented that it would be important to have pilot control of translucency and brightness of the indicators. Several pilots commented on the importance of the visual cues in the environment when landing on shipboard.

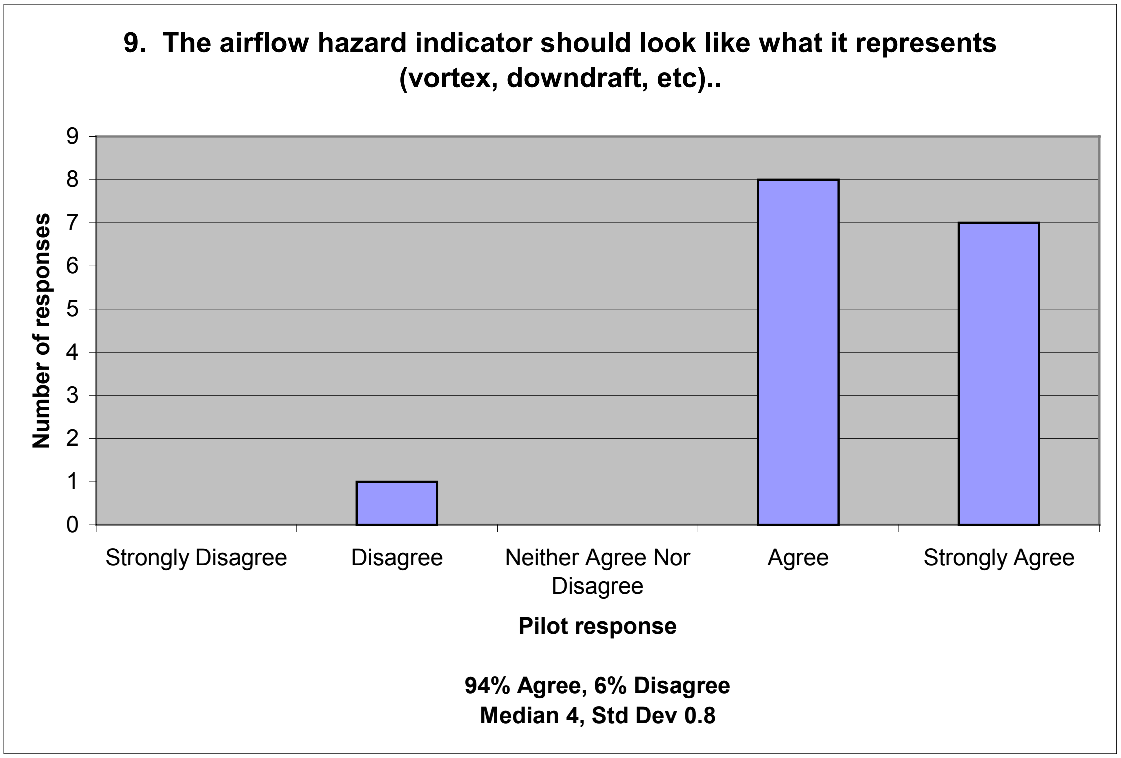
Table 33. Probe 8 Results



4.4.3.4.9 Probe 9. The airflow hazard indicator should look like what it represents (vortex, downdraft, etc).

Pilots were in agreement (Table 34) that the hazard indicator should look similar to the phenomenon it represents. However, when asked to elaborate, they gave widely differing answers. Several commented that they wanted wind arrows drawn on the surface of the object. One said that the pilots should be given a chart ahead of time decoding different symbologies that could be overlaid on the hazard indicator. Several pilots wanted more information than just a translucent cloud outlining the hazardous area. However, the pilots who wanted more information did not want it at all times during the approach. All of the pilots who stated a desire for more information (compared to the translucent cloud) said they wanted the additional detail at the beginning of the approach, but not at the end.

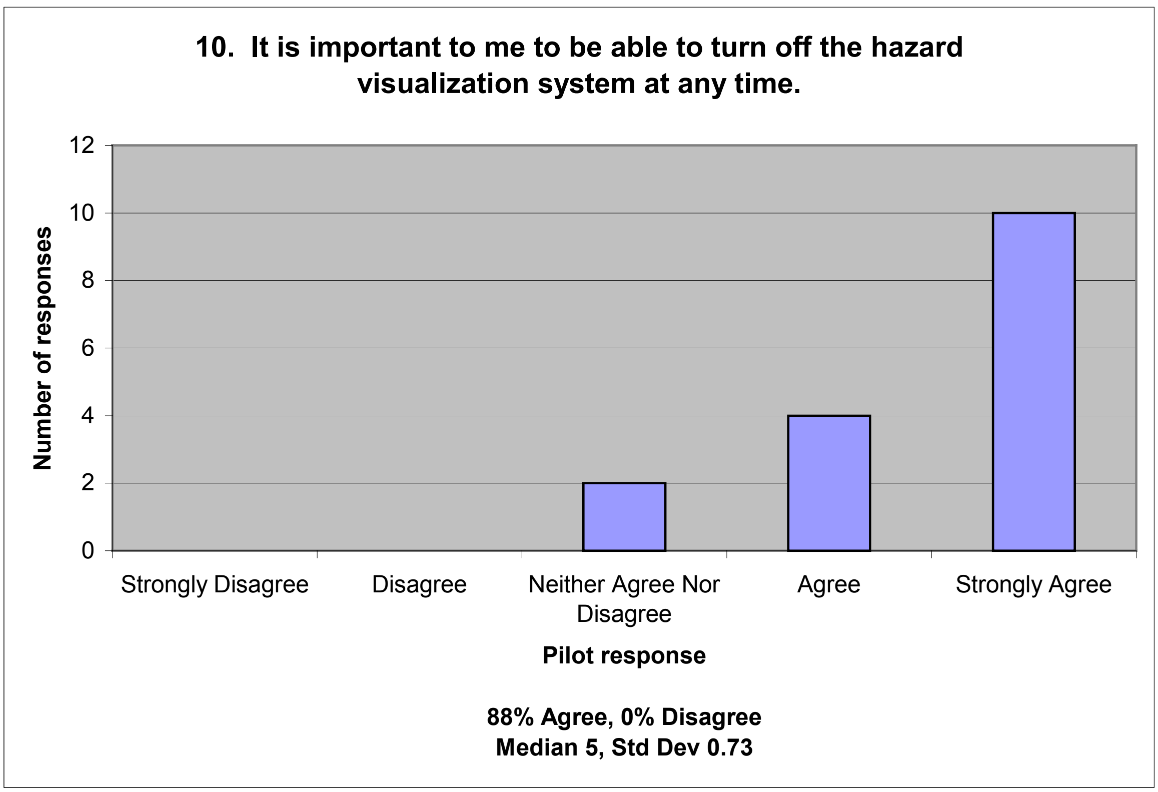
Table 34. Probe 9 Results



4.4.3.4.10 Probe 10. It is important to me to be able to turn off the hazard visualization system at any time.

Pilots had strong opinions (Table 35) about having control of the hazard indicating system. Many felt that the visual indicators must be turned off before they entered the space delineated by the indicators. One pilot said it felt “like flying into a garage” when he flew into the hazard indicator over landing spot 9 (in the Aft scenario).

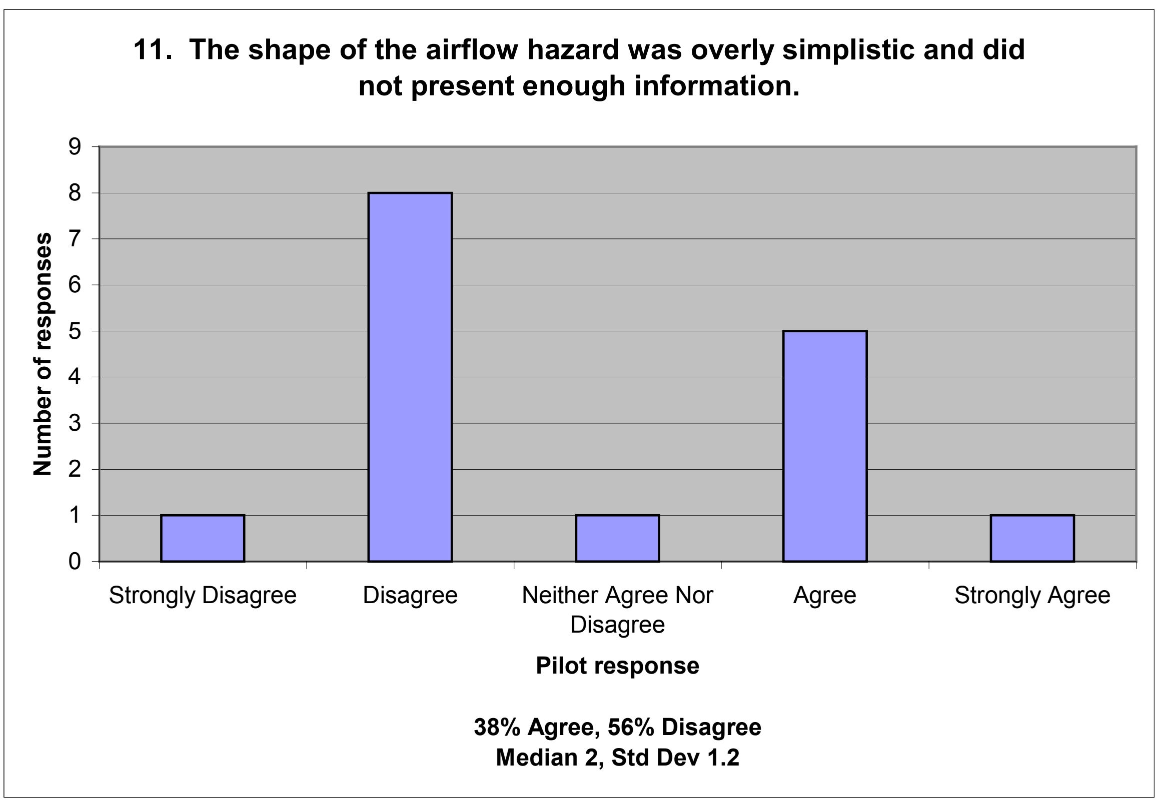
Table 35. Probe 10 Results



4.4.3.4.11 Probe 11. The shape of the airflow hazard was overly simplistic and did not present enough information.

Most of the pilots disagreed with this statement (Table 36). However, the bimodal distribution of responses coincides with pilot post-simulation commentary: it seemed that the pilots fell into two groups, one that wanted more information on the indicators, perhaps even some animation, and another that felt “the simpler, the better.” A few pilots commented that they wanted a quantitative value for airflow speed as well as the qualitative indication of whether the hazard was beyond aircraft limits.

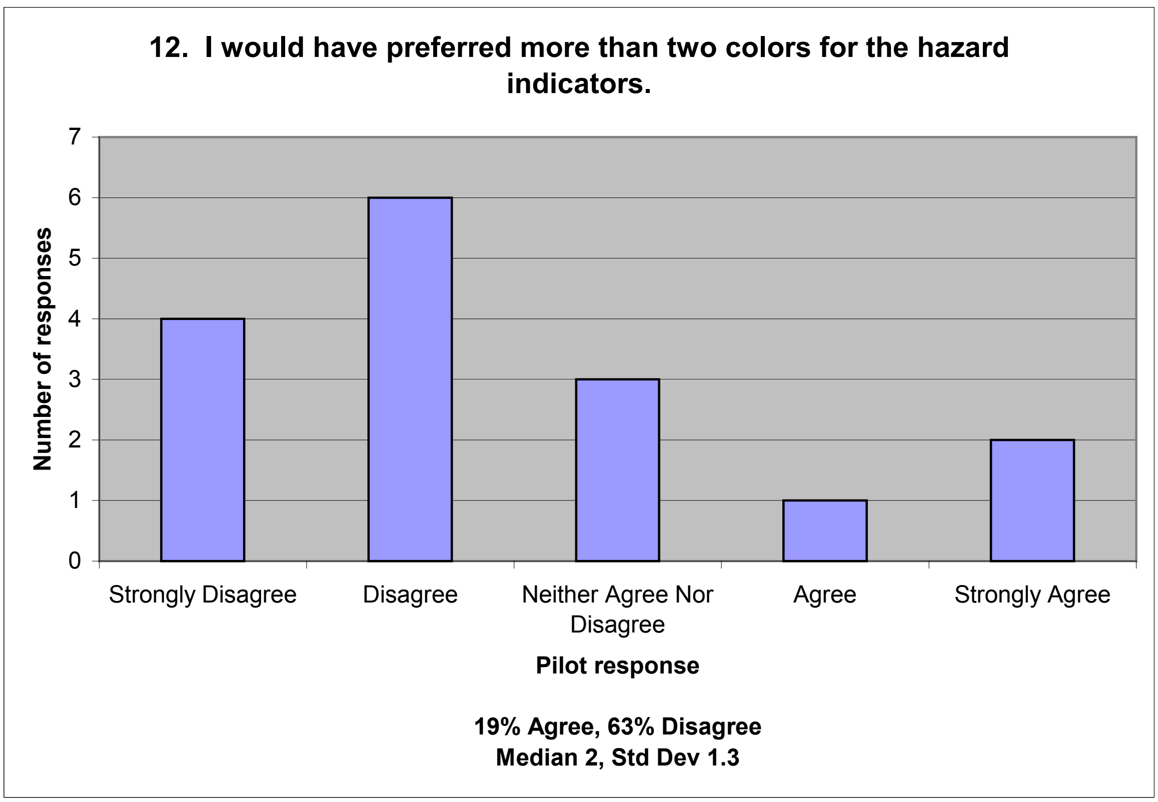
Table 36. Probe 11 Results



4.4.3.4.12 Probe 12. I would have preferred more than two colors for the hazard indicators.

Most of the pilots liked the simple, two-color system (Table 37). However, one of the pilots commented that he would have liked "to see a 'green' wind indicator for airflow not near aircraft limits." When asked if they wanted a multi-hue representation, every pilot queried said no.

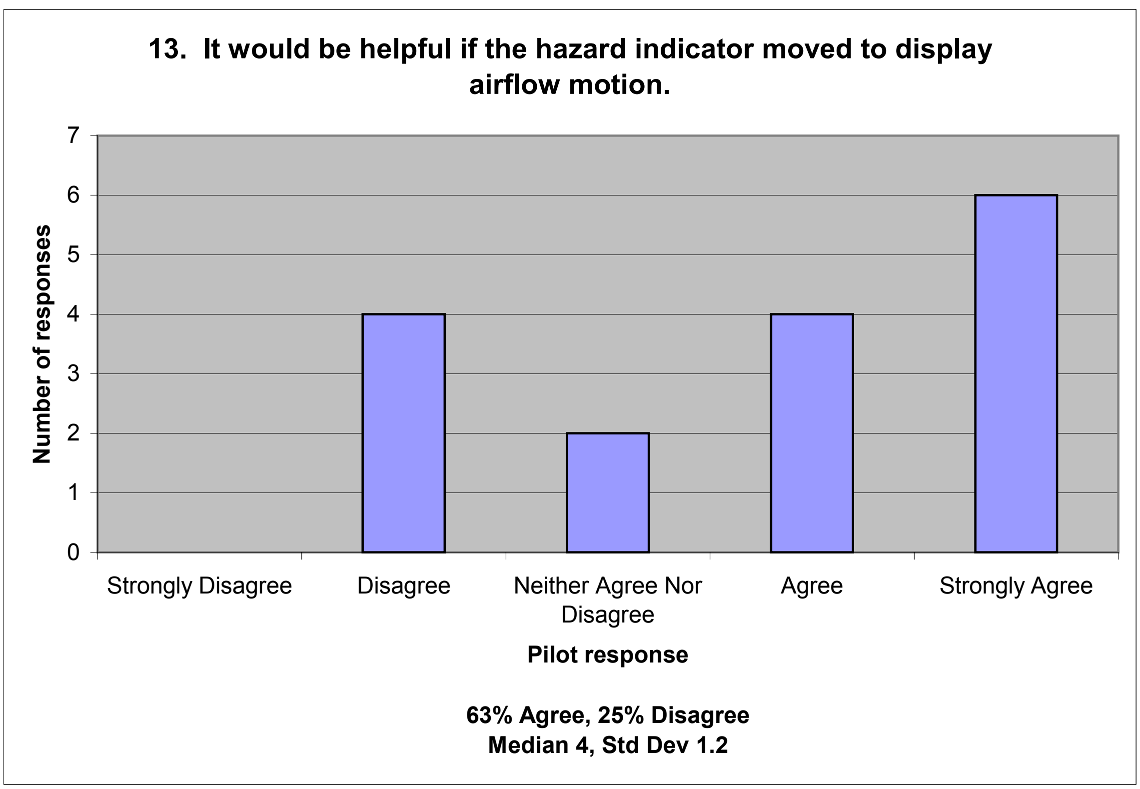
Table 37. Probe 12 Results



4.4.3.4.13 Probe 13. It would be helpful if the hazard indicator moved to display airflow motion.

(Table 38) illustrates the spread of opinions on indicator motion. Although the pilots were not as negative about motion or animation in this study as they were in the low-fidelity prototype, in this study we did not show them any moving indicators. The strong, almost visceral reaction of the pilots in the earlier study always occurred as they were viewing an animated indicator on the screen. Additionally, when a few of the pilots who agreed with this probe statement were queried as to the type of motion, they concurred that the animation should not be too rapid, and all of them wanted the ability to stop the animation, especially close to the end of the approach.

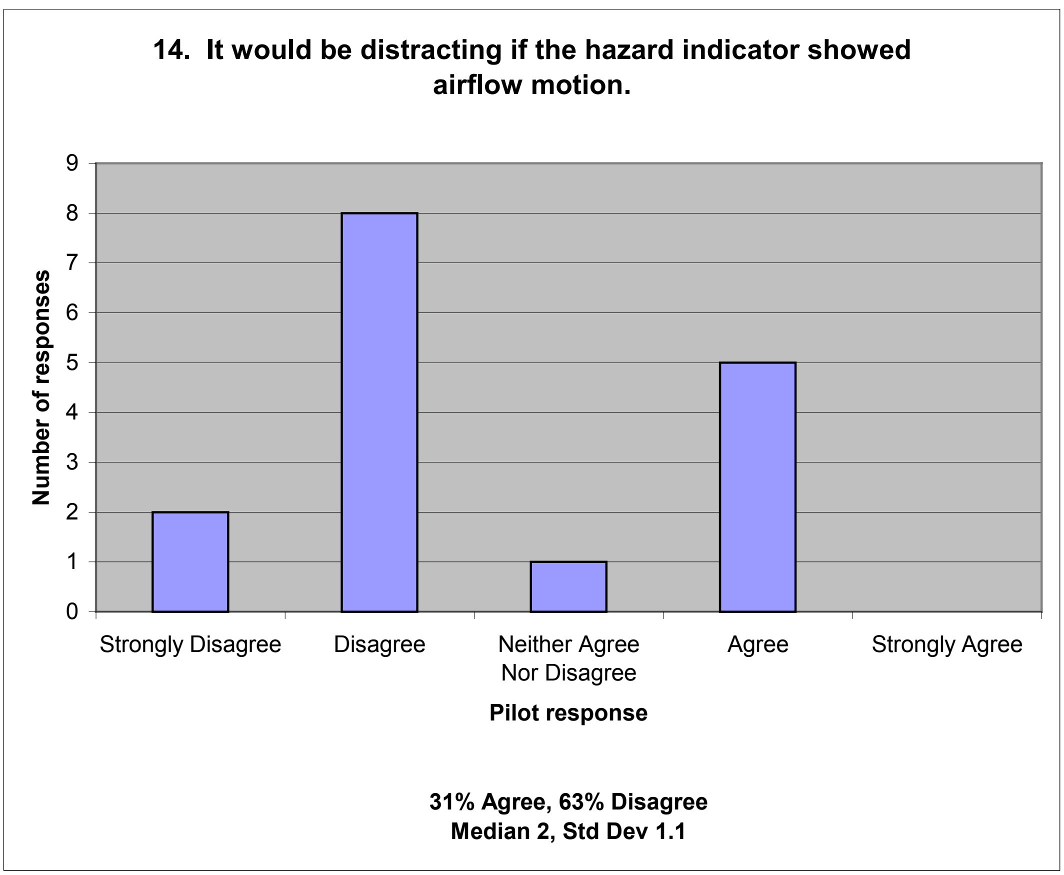
Table 38. Probe 13 Results



4.4.3.4.14 Probe 14. It would be distracting if the hazard indicator showed airflow motion.

Although the pilots mostly disagreed with this statement (Table 39), it must be noted that they were attempting to evaluate a hypothetical feature, and had not been given a chance to observe an indicator in motion. When the pilots who wanted airflow motion were asked for a reason, many stated that they wanted more information about the hazard at the beginning of the approach. Just as with probe 13, they concurred that they wanted to be able to turn off any motion.

Table 39. Probe 14 Results

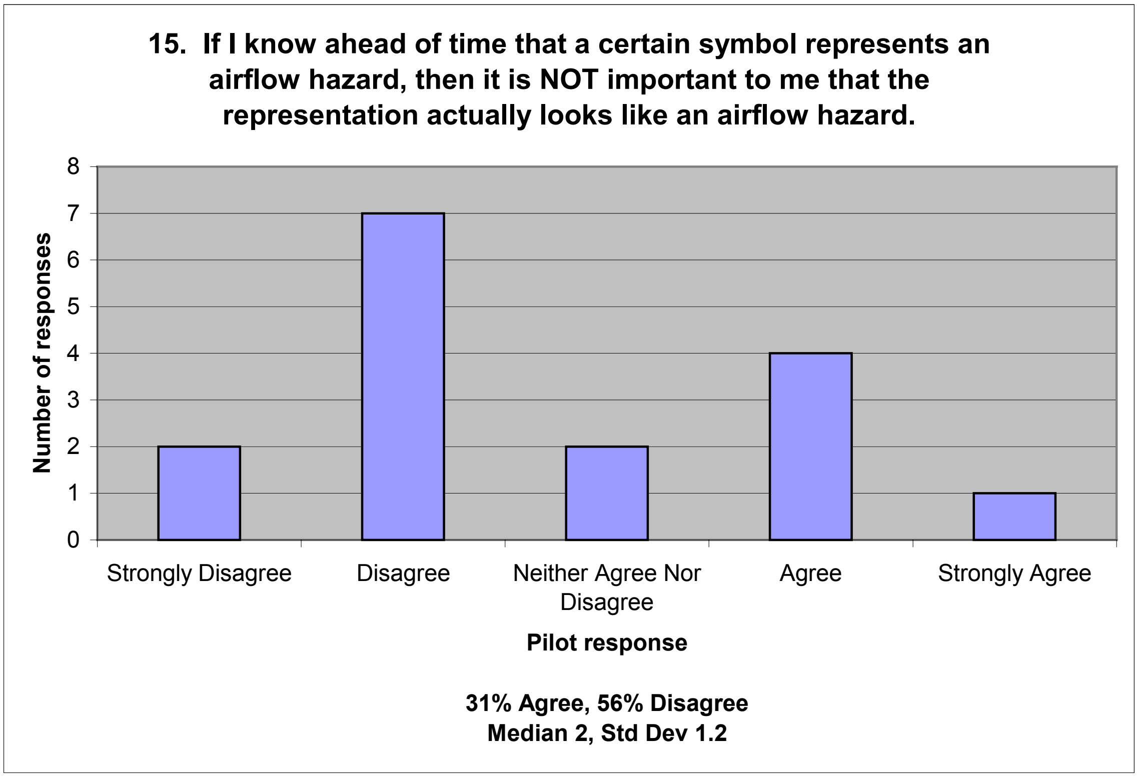


Probes 13 and 14 together indicate a need for further study on the use of animated indicators, as the benefits evidently anticipated by the pilots in the simulation study do not jibe with the strong aversion expressed by pilots in the low-fidelity prototype study.

4.4.3.4.15 Probe 15. If I know ahead of time that a certain symbol represents an airflow hazard, then it is NOT important to me that the representation actually looks like an airflow hazard.

Pilots mostly disagreed with this statement (Table 40), but it appeared that many of them found the question confusing; many slowed down as they attempted to answer it, and read the probe over again, sometimes out loud. Fortunately, there is another probe (probe 9, "The airflow hazard indicator should look like what it represents") which is partly redundant with this one. The results of probe 9 show good agreement that the indicator "should" look like an airflow hazard; probe 15 asks for agreement that the visual appearance is "NOT important". It is not clear to what extent the weaker result on probe 15 is due to participants struggling with the double negative (disagreeing that it is not important.)

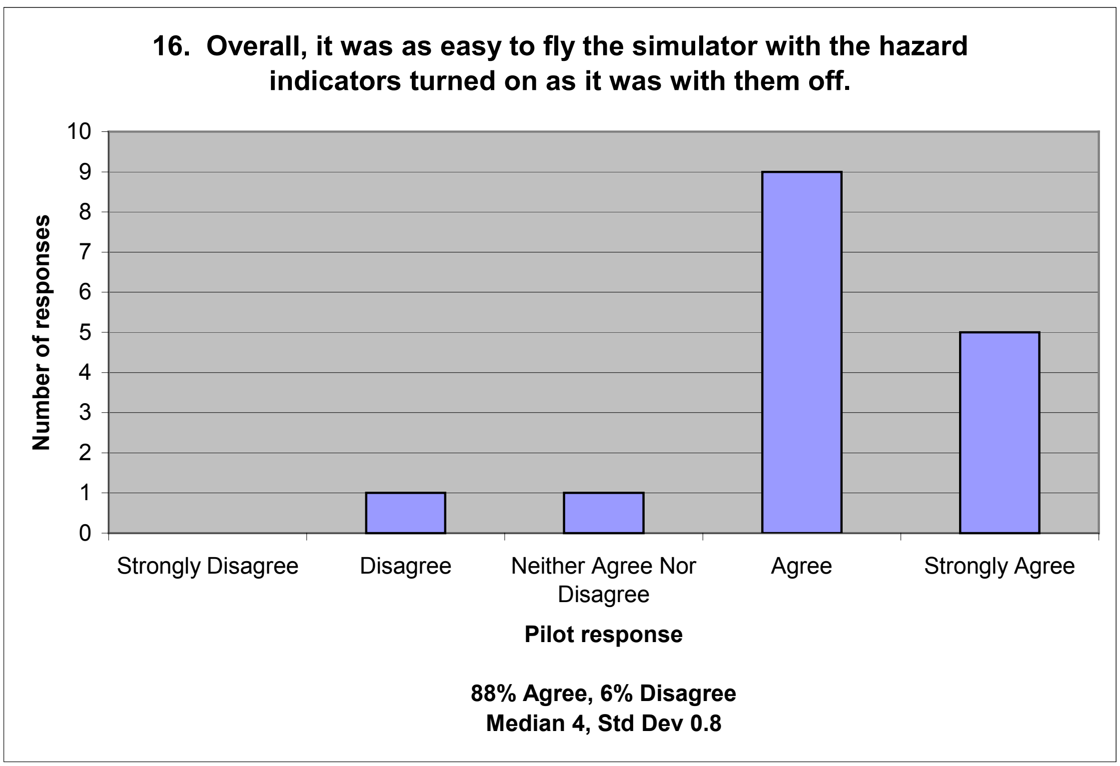
Table 40. Probe 15 Results



4.4.3.4.16 Probe 16. Overall, it was as easy to fly the simulator with the hazard indicators turned on as it was with them off.

The presence of the indicators did not cause difficulties for the pilots, neither in their subjective opinions as made evident in (Table 41), nor in their performance as illustrated by the test at landing difficulty 2.

Table 41. Probe 16 Results



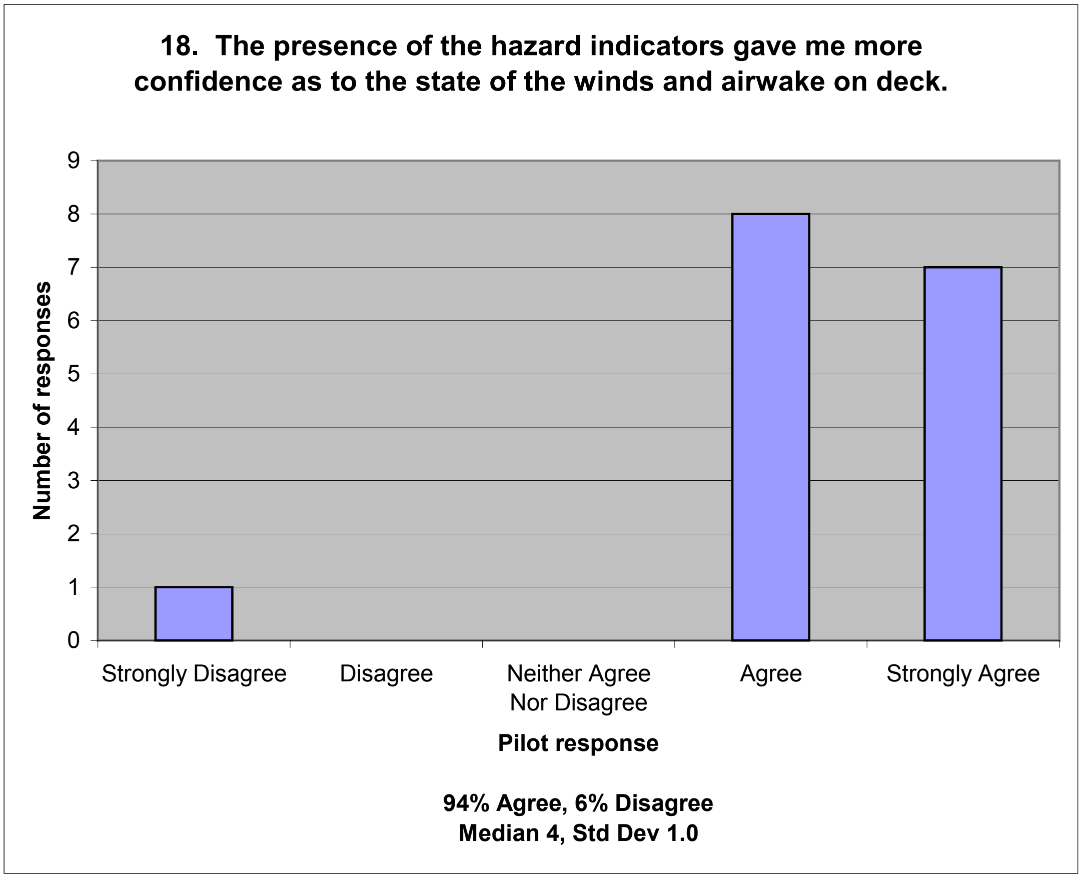
4.4.3.4.17 Probe 17. Over time, the display became easier to fly because my experience on the simulator increased.

This was discussed earlier, in (Table 15). The pilots almost unanimously agreed that they became better at flying the simulator as they developed more experience. However, this belief did not appear to be supported by their performance, at least as measured by crash rate. As we described earlier, the crash rate was almost identical during the first half of the approaches and the second half on a per-pilot basis.

4.4.3.4.18 Probe 18. The presence of the hazard indicators gave me more confidence as to the state of the winds and airwake on deck.

The pilots were almost unanimously in agreement with this statement (Table 42). The only pilot who disagreed was one of the most experienced pilots in our group, who stated that he already knew where all the hazardous areas were. We discuss this pilot's opinions further in the final section on pilot comments and suggestions.

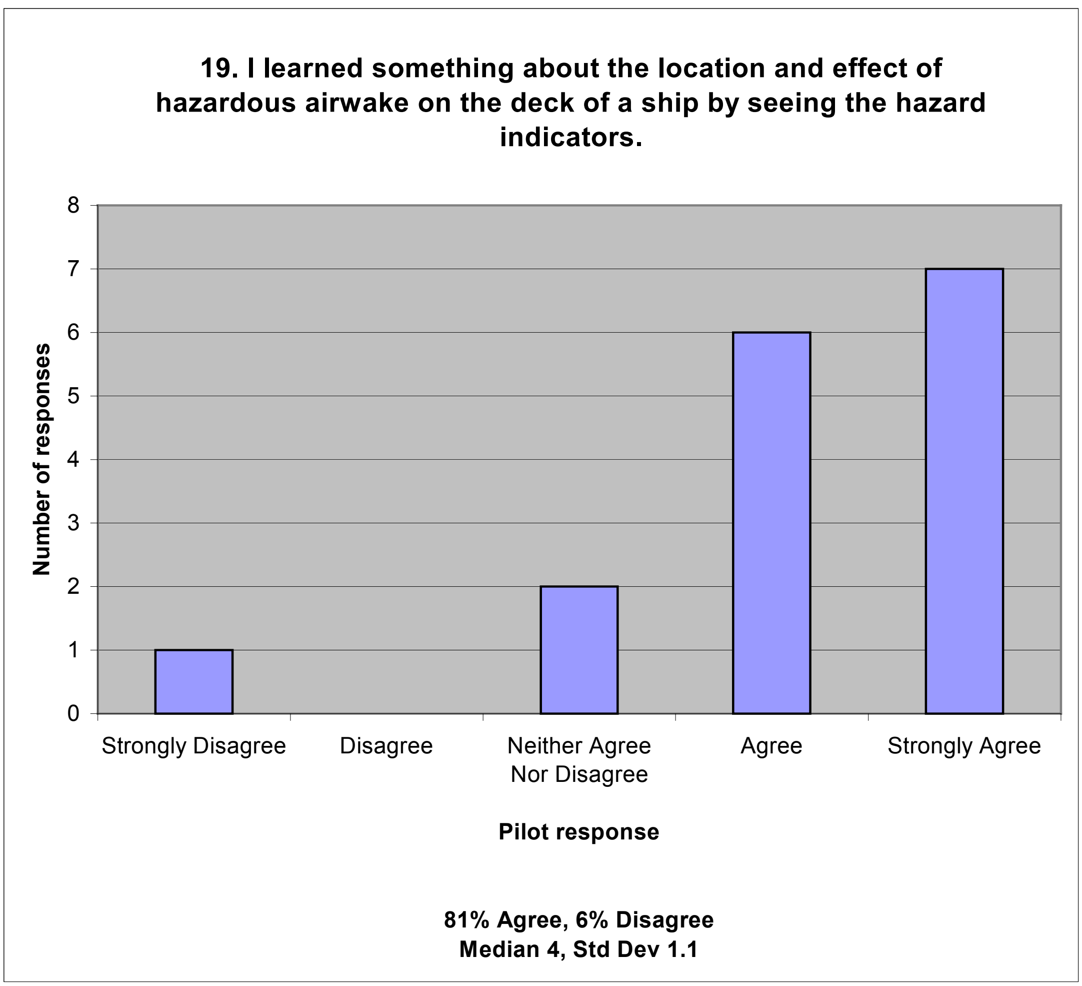
Table 42. Probe 18 Results



4.4.3.4.19 Probe 19. I learned something about the location and effect of hazardous airwake on the deck of a ship by seeing the hazard indicators.

Again, the pilots agreed with this statement (Table 43). The same experienced pilot that disagreed with probe 18 disagreed here; he said he already knew all about the location of hazardous airwake on ships. Indeed, he was one of the few pilots who did not crash at all during the simulation. The two who were neutral on this question were also relatively experienced.

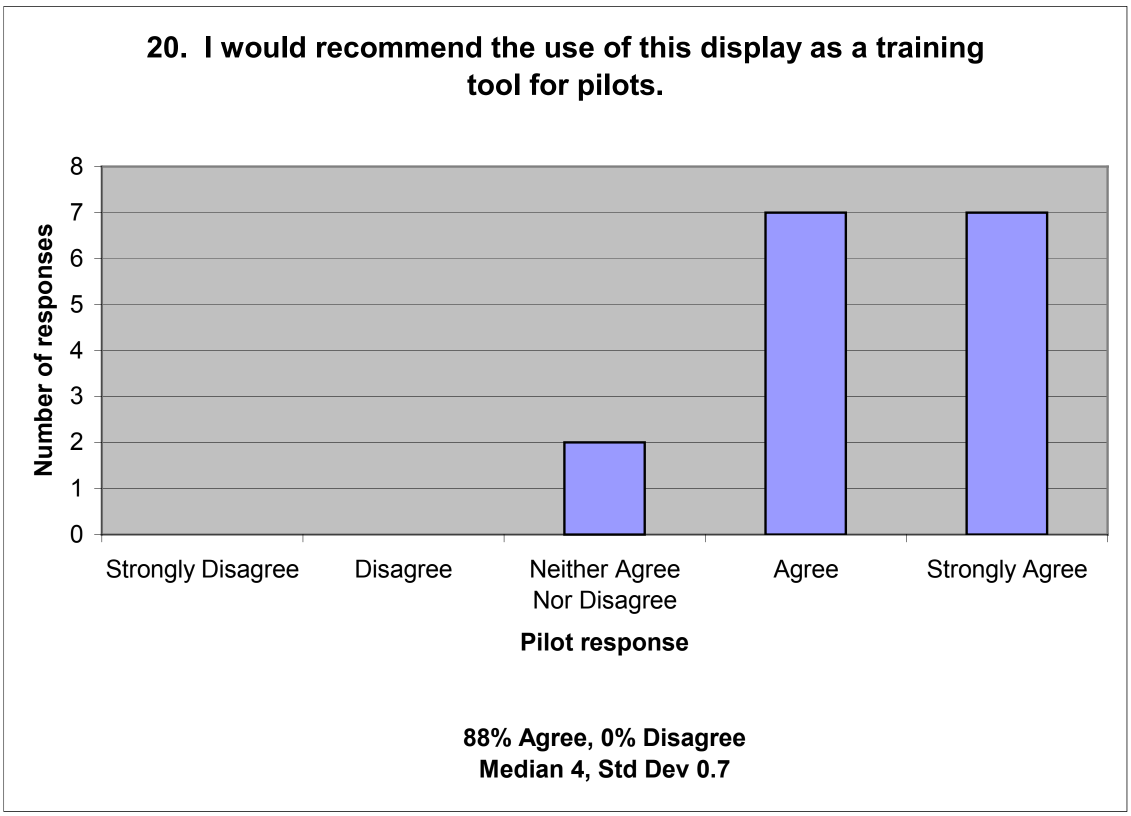
Table 43. Probe 19 Results



4.4.3.4.20 Probe 20. I would recommend the use of this display as a training tool for pilots.

The pilots were strongly in agreement on this statement (Table 44). Even one of the pilots who said they would not use the display themselves if it were available on their aircraft stated that they thought it would be a good training aid for less experienced pilots.

Table 44. Probe 20 Results



4.4.3.4.21 Probe 21. I would use this display system if it were available on my aircraft.

This was discussed earlier; see (Table 12). Overall, the fact that 81% of the participating pilots said they would use the system is very encouraging, and a strong indication that such a system would meet with pilot acceptance if it were implemented and installed in aircraft. Combined with the strong positive results in pilot performance in the simulation study, it is evident that further research into the implementation of an in-cockpit airflow hazard display system is called for.

4.4.3.4.22 Pilot comments and suggestions

At the end of our questionnaire, probe 22 was an open-ended question asking for their comments. We also gathered verbal commentary and suggestions from the pilots with a post-flight debrief. Several pilots commented extensively. In this section, we give some of their responses and suggestions.

As discussed earlier in the discussions on the responses to the post-simulation evaluations, there appeared to be a bimodal distribution of pilot opinions on whether the indicators were overly simplistic and needed to provide more information, or that more information would be distracting. We present quotes from two of them who illustrate the opposing viewpoints nicely:

One of the most experienced pilots in our study, who, however, did not have any helicopter shipboard landings, commented, “Interesting concept – needs some better depiction of what the hazard really is, i.e. vortex, rooster tail. Some velocity information would give the pilot some valuable lead information to anticipate what to do.”

On the other hand, a pilot with a moderate amount of experience but with many helicopter shipboard landings, said, "with all you have to do, landing... controlling your decel[eration]... especially at night... you don't want any distraction" in the form of animation or numeric indications in the hazard visualization.

It would be interesting to conduct a further study, where different types of hazard indicators, some with an indication of airflow motion, some animated, some with numeric readouts, were compared with the baseline.

Another area for further research lies in making the display adaptive. Several pilots commented that they wanted more detail at the beginning of the approach and less at the end. To that end, perhaps an adaptive display might be successful. The display could adapt based on where the pilot was in the approach, or could be more sophisticated and track pilot workload through physiological sensors, or could just have several modes that could be selected by the pilot.

One pilot said he would prefer a hazard indicator that was not in the visual field. Another stated that night operations were more important than day VFR (Visual Flight Rules), and that the indicating system must be studied at night for it to be useful. Night operations would be another fertile area for future research.

Numerous pilots commented on the quality of the flight simulation. "The simulation was good... in the [simulator] we use, as soon as you get off the ground, you punch the autopilot." Another said, "[This simulator] is as good as any I've flown." And one said, "It's an order of magnitude better than any others I have experience with." There were also suggestions for improvement in the simulation, some of which could be implemented in further studies. More details on pilot comments on the simulator are given in Appendix A.3.

One pilot mentioned "sensor fusion" – a "hot topic in avionics research." This refers to the technique of melding data received from sensors (such as forward-looking infrared sensors or radar altimeters) with each other or with synthetic vision displays [2]. It would be interesting to study methods of integrating visual hazard indicators with out-the-window views or synthetic vision systems.

Many pilots spontaneously mentioned helicopter accidents that they felt could have been avoided if the pilots had had a system like this one. One pilot mentioned the Mount Hood Pave Hawk crash in 2002, where a helicopter in the process of rescuing nine hikers trapped in a crevasse on a mountaintop suddenly crashed [22]. The weather was beautiful and sunny, but there were gusty winds, as is typical around a mountaintop. This pilot believed that unseen turbulence and/or downdrafts beyond the capability of the helicopter were the likely causes of the crash.

Another commented that in his work as a medevac pilot, he hated landing on top of Stanford Hospital, "especially at night." "There's always a vortex there," he said.

One pilot had a relative who flew helicopters in firefighting. Backdrafts and up- and downdrafts cause tremendous dangers for firefighting pilots. A system like this "could really make a difference."

4.5 Conclusions

In this chapter, we have described the experiment setup, protocol, and results of a high fidelity flight simulation usability study. Our results are positive, and confirm our thesis statement, "Simple, real-time visualization of airflow can improve helicopter pilot landing performance." Generally enthusiastic comments from our domain experts confirm our belief that such a system could greatly benefit aviation safety.

Chapter 5 ■

Conclusions and Further Work

5.1 Summary of Results

In this dissertation, we have discussed the problems that invisible airflow hazards pose to pilots, and how new developments in sensor technology suggest a possible solution – provided, however, that the sensor data can be effectively presented to the pilot. We focused, for reasons explained in Chapter 1, on helicopter pilots performing shipboard landings. We provided a survey of related work (Chapter 2), and described our initial ideas for a solution. We then described the process of user-centered design of an airflow hazard display system, beginning with a low-fidelity prototype (Chapter 3) and continuing with a three-phase high-fidelity flight simulation usability study (Chapter 4).

The results of the study, where information visualization of airflow hazards was presented to helicopter pilots in a highly realistic simulator, showed a significant improvement in their ability to land safely under turbulent conditions when supplied with the visualization interface. In this experiment, we discovered that the type of visualization needed to improve operational safety was much simpler than that needed for analysis of airflow hazards, providing an example in which the appropriate visualization differs for analysis vs. presentation.

This study also validated the use of HCI techniques and user-centered design. By providing for usability testing early in the design and obtaining feedback from domain experts, we were able to avoid the potentially costly mistake of developing an overly elaborate interface based on existing flow visualization techniques which could have degraded (rather than enhanced) pilot operations.

The enthusiastic response we received from the pilots testing the system and the strong positive results from our simulation study indicate that such an airflow hazard visualization system could improve aviation safety, especially because it appears that pilots would actually use the system in the cockpit. Systems of this type could also be developed for other aviation applications.

5.2 Further Work

Judging from the high level of pilot interest, and the many pilot suggestions for further directions, there are many opportunities for future research in the area of airflow hazard visualization. Additionally, this work could be expanded to study methods of information visualization in other safety-critical applications.

5.2.1 Further data analysis

We recorded over 50 simulator variables at 10 Hz on every landing approach, such as aircraft position and acceleration, control (cyclic, collective, and pedal) position and acceleration, external forces on the landing gear throughout the approach, and engine torque. In all, we collected over 22 million data points, in which additional patterns could likely be discovered by further study. Some areas of potential further data analysis might include:

1. Graphing and analyzing cyclic, collective, and pedal motion and acceleration during the approach, in order to discover if the presence or absence of the hazard indicators has any effect on pilot workload. Apply power spectrum analysis to the control input data. Are the amplitude and frequency of the control motions greater if a hazard indicator is present or absent?
2. Comparing the flight paths during the approach, including flight path deviations and landing dispersion (distance from target landing site) when pilots are flying either with or without hazard indicators. Do pilots deviate from a standard approach if they are given an indication there is hazardous airflow in their flight path? How do such deviations compare to the number of crashes? Is landing dispersion greater or smaller if a visual hazard is presented to the pilot?
3. Apply a quantitative measure to landing quality rather than just the binary "crash/no crash." Study and analyze the descent rate on touchdown, for example, or measure the landing gear forces on touchdown in addition to the descent rate.

5.2.2 Further studies

Many possible studies were indicated by pilot suggestions for improvement to the system.

The bimodal distribution of pilots' opinions concerning motion or animation in the hazard indicators demonstrates that it might be productive to conduct a further study, where several different types of hazard indicators, some with a static indication of airflow motion, some animated, some with numeric readouts, were compared with the baseline. The concentration of positive opinions in pilots who did not actually see animation suggests a perceived potential benefit; additional experiments might indicate specific display characteristics that realize or negate that benefit.

The thesis demonstrated the efficacy of a new type of hazard indicator, but did not quantitatively compare it against other methods. Another study that should be undertaken is to compare our system (a scene-linked three-dimension hazard indicator that precisely specifies the position of the airflow hazard) with a simpler and more conventional binary warning, such as an auditory signal, or a light in the cockpit.

Several pilots expressed a desire for an adaptive display—one that presented more detailed flow information at the beginning of the landing approach, but changed to the static (but still scene-linked) visualization as the approach progressed and pilot workload increased. An open question is how and when to adapt the display to pilot state. The display could adapt based on the aircraft's situation in the approach, or could adapt to the pilots' situation (e.g. a more sophisticated tracking of pilot workload through physiological sensors), or could simply have several modes selectable by the pilot. If adaptation is automatic, then both the selection of appropriate criteria (input features) and the adaptation algorithm would require investigation.

5.2.3 System development and deployment

Steps could be taken toward actually implementing an airflow hazard visualization system in aircraft; the system presented in this thesis is a component (the visualization front end) of such a system, and would require integration with other components. For example, through collaboration with developers of lidar sensors, the visualization system could be connected to actual real-time sensor data.

There are also many possibilities for integration with existing synthetic vision systems, or with augmented reality systems for military aircraft, such as predicting weaponry range.

Such integration would, in turn, provide further information about the performance of each component, likely leading to additional improvements.

5.2.4 Background or more basic research

Several of the issues that will need to be resolved, before a system such as envisioned in this thesis could be fully realized, are themselves areas for additional research. These areas include augmented reality image registration, sensor fusion, and methods of measuring the user's physiological state and workload for driving an adaptive display (for example, with eye tracking devices).

5.2.5 Extensions to other areas

This study points to the success of HCI techniques in operationally stressful arenas. Further work is called for in applying HCI techniques to areas such as information visualization for emergency response.

Space exploration is an operationally stressful environment in which hazards or opportunities may be invisible (e.g. radiation, objects over the horizon or occluded by equipment) and in which a high degree of technical support for crewmembers is expected and appropriate. Therefore, the arguments for applying these HCI techniques to helicopter landings may be even more valid for space explorers.

Further work could be performed on the presentation of data from multiple sources, e.g. the fusion of real-time sensor data with information stored in databases.

This work could be extended into other aviation-related activities, including unmanned aerial vehicles (UAVs) (for example, as a method of efficiently presenting potential hazards to an operator overseeing multiple UAVs), helicopter search and rescue (airflow hazards in canyons and clearings or at high altitude), aerial firefighting (backdraft visualization), offshore oil platform operations, or fixed-wing operations.

Finally, there could be extensions into the visualization of hazards for automobile drivers, or other safety-critical applications.

5.3 Conclusions

Over the course of work on this thesis, we applied information visualization knowledge and user-centered design techniques to a real-world problem that has caused loss of human life and hundreds of millions of dollars in damaged aircraft over the past few decades. We learned much from the process as well as from the end results of our final usability study. In particular, our participants' commentary pointed us to many potentially fruitful directions to engage in further research. The strongly positive results we obtained indicate that subsequent investigations into hazard visualization could lead to the development of systems with the potential to greatly increase aviation safety.

Although we may not necessarily have found the Holy Grail as one of our participant pilots suggested, visualization of unseen hazards of any type – airflow, radiation, weaponry within range – may lead us along the track of the Grail: building an aviation and space system where the accident rate drops asymptotically towards zero.

Appendices

In this section the scripts, forms, and other materials used in the usability studies are collected. First, we include the materials for the low-fidelity prototype, and then for the flight simulation study.

A.1 Materials for Low-Fidelity Prototype

In this section we include our notes on designing the low-fidelity prototype and usability study, and then include the script we used in operating the prototype and discussing it with the participants.

A.1.1 Low-Fidelity Prototype Description

Prototype will consist of a brief animation from the pilot's eye view, what a Navy helicopter pilot would see coming in for a landing on a ship, or the view from sitting on deck while preparing to start engine. Hazard indicators for vortices, downdrafts, exhaust plumes, wind shear etc. will be created in 3D using a graphics library that supports animation.

Notes: no pilot control of animation, 3D images need not be fully realized. Purpose of low-fidelity prototype is a "quick and dirty" view of final system, to present to users to get their input on an iterative basis for user-centered design.

Questions:

1. which images and colors to use?

2. should images/colors change?

3. when should images appear? Disappear?

4. aural signals?

5. how to detect 3rd dimension, exact location of hazard in 3-space?

Hazard indicators:

Static:

1. red transparent "cloud"

2. rectangular box to indicate danger zone

3. series of filled ovals/rectangles

4. series of outlined ovals/rectangles

5. opaque versions of above

6. different colors of above
7. hedgehog vector plots
8. spiral
9. other?

Dynamic:

10. moving spiral
11. unsteady flow visualization techniques:
    a. streamlines
    b. streaklines, timelines
    c. spot noise
    d. flow volumes (release of smoke into vector field)
    e. line bundles
    f. other scientific visualization techniques
12. other?

Design scenarios with flight test engineer to get script correct. Have 3 pilots “fly” scenarios. Have each of them fill out consent forms and a pre-test questionnaire about their background. Take notes, have them make comments. Have them fill out a post-test questionnaire. Tape the test.

A.1.2 Low-Fidelity Prototype Usability Tests Script

15 November 2003

Usability study is scheduled for November 18-19 and 25-26, 2003. Dry run scheduled on Tuesday, November 18, 2003 with a Navy flight test engineer. A low-fidelity prototype has been implemented in Rhino, a 3D CAD modeling program. At first we planned to develop the low-fi prototype using paper printouts of helicopter flight simulator screen shots and other two-dimensional paper aids. But after discussions with helicopter flight test engineers it was determined that a three-dimensional prototype was necessary to give the participants sufficient information to enable them to be helpful in providing input to the design.

We considered various prototyping tools, including MS Flight Simulator, WildTangent, a number of VRML-based tools, Java, and Flash. We settled upon Rhino because of easy access to ship models, our familiarity with the system, and the ease of creating three-dimensional objects in a relatively short time to support interactive prototyping.

We hope to have at least three participants, hopefully all helicopter pilots with a significant number of shipboard landings. Each interview will last about one hour, and will be videotaped with the participant's permission.

Script

1. Welcome participant and thank them for coming. Get them seated and comfortable. Offer them cookies and bottled water. Brief explanation/overview of system and introduction of Cecilia. "I'm doing a Ph.D. thesis in computer science at U.C. Berkeley, developing a prototype interface for flight-deck visualization of ship airwake hazards such as vortices, downdrafts, wind shear, or hot exhaust plumes, and because of your experience, we'd like you to help us with the early-stage design. We're going to show you a series of animations simulating the final approach to landing of a helicopter on a Spruance-class destroyer, and ask for your feedback on different types of hazard indicators. This will take about an hour. But before we get started, there's some paperwork you need to fill out."

2. Paperwork required. "What this says is a brief explanation of what we'll be doing, and that participation is completely voluntary; you can withdraw at any time. It states that any records we keep will be kept confidential. Your name will not appear in any reports we might publish. It's understood that you don't represent your employer officially, but you have valuable experience that can hopefully help us provide something useful to helicopter pilots." Hand participant the consent form, records release form, and a questionnaire (name, address, phone number, email address. Years of helicopter experience, number of helicopter flight hours, shipboard experience, types of helicopters flown, main types of ships landed on (carrier, amphibious assault, surface combatant, other). Have you ever encountered any non-mechanical difficulties during a shipboard landing? Are you left-handed? Are you color-blind?) Explain each form; give them time to read it before they sign. Ask them if they have any questions.

3. Run the videos. "I've put together some videos to give some motivation as to why a system like this might be useful." Show videos, discuss.

4. Begin experiment. Load up prototype. "If you want to see any of the approaches again, or have me reposition the ship, feel free to interrupt and ask for what you need."

5. "This is what's known as a low-fidelity prototype. It is not supposed to be completely realistic. The purpose of this prototype is to obtain early-stage input into the final design from you, the intended user. The system will go through many iterations, hopefully with input from users at each step of the way. This is our first cut at the prototype, and we welcome any and all input. Please feel free to make any comments, criticisms, suggestions for improvement, or voice any opinions at any time during this procedure."

6. "Under different wind conditions, sea states, helicopter gross weights, and other factors, invisible airflow hazards such as vortices, downdrafts, wind shear, hot exhaust plumes, etc. may be present near the shipboard landing zone. The purpose of our research is to determine which of these factors may present a hazard to a particular helicopter on a given landing, if presenting this information to the pilot before landing could increase safety, and how best to get the information to the pilot. Today we're going to show you a number of different scenarios of how normally invisible airflow hazards could be visualized, and I'll ask a number of questions about these images and other possible techniques. I may ask you to imagine a situation which is not present in the low-fidelity prototype in front of you, in order to determine if it makes sense to add certain features to the final system."

7. “Imagine that you are flying a helicopter, about to begin the final approach to land on a Spruance-class destroyer, specifically USS Cushing, DD985. You have a head-up display of a system that can visualize airflow hazards that may be present around or near your intended shipboard landing site. The system can be turned on or off at the pilot’s option. You have just been cleared to land by the HCO (helo control officer) and this is what you see on a stern approach.”

8. Start run 1, cloud sequence (varying color, transparency, texture)

9. Questions on run 1:

a. Would it be useful to know that some kind of airflow hazard, such as a vortex, extreme downwards flow, wind shear, hot exhaust, or even just a burble, were present in that area shown in red (yellow, green, gray, blue)?

b. We’re going to show you a number of indicators (in this run), varying texture, color and transparency, and get your feedback.

c. Does the color of the hazard matter?

d. If so, what use of colors would you suggest?

e. Would it make sense to have a range of colors depending on the degree of the hazard?

f. Any other comments about the color?

g. Does the transparency of the object matter?

h. If so, what use of transparency would you suggest?

i. Would it make sense to have a range of transparencies depending on the degree of the hazard?

j. Would applying a texture to the cloud, such as lines of force, arrows in the direction of airflow motion, be useful or not?

k. Would other visual indicators, such as arrows sticking out of the cloud indicating airflow direction, or numeric indicators to show airflow velocity, be helpful? Why or why not?

Start run 1b (shadows)

l. Depth cueing. Does placing a shadow on the deck under the hazard indicator help you locate it in three-dimensional space? Are there any other types of depth cue that would be helpful?

10. Start run 2, boxes (varying transparency, texture, shadows)

11. Questions on run 2:

a. Is the shape of this hazard indicator better or worse than the previous shape? Why?

b. Any comments on transparency or texture?

c. Other comments?

12. Start run 3, ovals (varying filled or open, transparent or opaque).

13. Questions on run 3:

a. Is the shape of this hazard indicator better or worse than the previous shapes? Why?

b. Does it make a difference if the ovals are filled or open?

c. If the ovals are filled, does transparency matter?

d. Other comments?

14. Start run 4, rectangles (varying filled or open, transparent or opaque).

15. Questions on run 4:

a. Is the shape of this hazard indicator better or worse than the previous shapes? Why?

b. Does it make a difference if the rectangles are filled or open?

c. If the rectangles are filled, does transparency matter?

d. Other comments?

16. Start run 5, spirals (varying color and aspect ratio).

17. Questions on run 5:

a. Is the shape of this hazard indicator better or worse than the previous shapes? Why?

b. If the spiral were in motion, would it matter?

c. Would the speed of the spiral make a difference?

d. Would it help if the degree of hazard were indicated by the thickness of the spiral, or the speed of motion of the spiral? Any other suggestions for degree of hazard?

e. Other comments?

18. General comments on the static hazard indicators.

a. Could any of these indicators be useful to you?

b. In addition to always being able to toggle these indicators on or off, would you like them to default to always on no matter where you are in the landing approach? Or should they only be visible at certain stages of the landing approach?

c. When should images appear/disappear? Starting final approach? On short final? As you're touching down? As you enter the hazard zone?

d. When should images/colors change? How indicate a change in status? If you change your course, should images/colors change?

e. What about auditory signals to accompany the visualization?

19. "Now we're going to show you other types of visualizations for airflow, and I'd like you to imagine these images in motion over the ship as you come in to land. Before we start, though, I'd like to get your opinion about the use of animation to help understand more about the airwake over the ship. For example, what if this spiral were slowly rotating in the direction of airflow, simulating a vortex."

20. Questions about animation:

a. Do you think animation is helpful, distracting, both, or neither?

b. What degree or speed of motion would you prefer?

c. Would you prefer the visualization to be in motion all the time, just as air is in motion all the time?

d. Or would you only prefer motion when there is a change in the degree or position of the hazard?

e. Do you prefer an exact representation of the hazard, or just an approximate idealization of the hazard? Why?

21. Start showing web sites:

a. http://cromagnon.stanford.edu/jship/

b. http://www.llnl.gov/graphics/movies/Flowcor320.ApV.qt

Show movie of water channel or smoke flow over a ship.

c. http://www.llnl.gov/graphics/movies/VandS320ApV.qt

d. http://www.llnl.gov/graphics/gifs/TornadoLines2_600.gif

e. Others

22. Questions for each of these web sites:

a. Do you think a visualization like this one over a ship deck would be helpful, distracting, both, or neither?

b. What degree or speed of motion would you prefer?

a. Compare with other dynamic visualizations

23. Final comments. Ask participant for final comments, if they want to see any of the visualizations again. Ask questions again: make sure I understand what they've been saying. I used 5 variables: shape, transparency, texture, color, and motion. Ask about each. "What are your thoughts on the use of _____ for visualizing airwake?" Depth and height cueing. "Do you have suggestions for a better way?"

a. "How would you evaluate the potential of a system like this for improving shipboard safety?"

b. "Do you have any advice for follow-on parts of this project?"

b. "Would it help to do a piloted simulation next?"

c. Recommendations of other systems that are related, or that we should know about?

d. Potential applications for non-shipboard landings?

24. Thank them for their time and ask if they'd be willing to come in for a follow-up study.

25. Call pilot back in a couple of days – to thank them and get more opinions. "We'll be letting you know when the next stage will take place, if you're interested."

A.2 Materials for Flight Simulation Usability Study

This section contains materials used in the ART flight simulation usability study.

A.2.1 Scripts and Briefings

A.2.1.1 Overall Script for Airflow Hazard Simulator Study

July-Sept, 2004

1. **Welcome.** Thank participant for coming. Get them seated at conference table and comfortable. Offer them refreshments and bottled water. Let them know where the restroom is. Brief explanation/overview of system and introduction of experimenters.

2. **Paperwork**. Hand participant the consent form, records release form, and the pilot information. Explain each form; give them time to read it before they sign. Ask them if they have any questions.

3. **Pre-Flight.** Read them the Participant Pre-Flight Briefing script

4. **During Flight**. Give them the cockpit briefing. Review the Approach Form. Ask for questions. Operate the simulator, take notes on Approach Form

5. **Post-Flight.** Read them the Participant Post-Flight Debrief script. Ask for their opinions.

6. **Thanks.** Thank them for helping with the experiment.

Participant Pre-Flight Briefing
Sim Test – Phase 3 – July-Sept 2004

Under different wind conditions, sea states, helicopter gross weights, and other factors, invisible airflow hazards such as vortices, downdrafts, wind shear, hot exhaust plumes, etc. may be present near the shipboard landing zone. The purpose of our research is to determine whether displaying a visual indication of the presence and location of such hazards on a head-up display can improve helicopter flight safety.

Imagine that you are flying a helicopter similar to an H-60, about to begin the final approach to land on an LHA type ship. You have a head-up display of a system that can detect and visualize airflow hazards that may be present around or near your intended shipboard landing site. The system can be turned on or off at the pilot's option.

You are going to fly about 28 final approaches to land on the deck of a moving LHA-type ship, at 4 different landing spots. You'll be given an orientation flight consisting of first, a practice flight to get used to the controls of the simulator, suggest flying from a hover to straight and level cruise. Then practice 4 approaches, each one to a different spot. During the simulator test, you'll be given a clearance to land on a particular spot, and the winds on deck (speed and direction). Sometimes you will see a red or yellow transparent hazard indicator along your intended flight path, and sometimes you will not. If you don't see a hazard indicator, it either means the winds are such that there is no hazard, or that there IS a hazard but the system is not turned on. By the way, high winds are not necessarily correlated with an airflow hazard in this experiment.

Here is a drawing of the landing spots on the ship and what the approaches might look like. (Show drawing.)

Here is a picture of what a hazard might look like in our interface. (Show picture of hazard indicator.) The shape of the indicator will roughly indicate the area where hazardous airflow might be found. The type of airflow hazard (such as downdrafts, turbulence, vortices, etc.) will not be indicated. The color of the indicator shows the intensity of the hazardous airflow. Yellow indicates caution: a hazard that may cause difficulty in landing, but that is likely not beyond the capabilities of the aircraft. You can continue the approach with caution. Red indicates danger: a hazard that is probably beyond the capabilities of the aircraft and a safe landing is not probable. You should abort the approach and wave off.

There are two bugs in the simulator that will not exist in the final system: On the projection screen, colors look grayed out, and the red and yellow transparent shapes will not look fully saturated. This is merely an artifact of the projection screen. In the final system, the pilot will be able to manually adjust the brightness of the hazard indicators depending upon pilot preference or the ambient light. Also, you will notice that the ship markings flash in the simulator. Again, this is a simulator error and will not be present in the final system.

Here is a picture of the helicopter instrument panel. (Show picture of panel. Describe each instrument.) Do you have any questions about the instrument panel?

Each approach in the simulation will be started by a human operator. You can give the operator voice commands. You can turn the hazard indicator system off by saying "Hazard Off." As you approach the indicators, if you choose, they will be turned off so that you can make the landing without the distraction of the transparent bubble around you. You can also say, "Wave Off," if you wish to terminate the approach; or

“Landing Complete,” if you’ve landed and you want to terminate the simulation. (The simulated helicopter doesn’t have brakes, so sometimes it’s best to just have the operator stop the simulator as soon as you land.) Please feel free to stop at any time if you need to.

After each landing, we’re going to ask you for two ratings: (1) the objective difficulty of the approach on a scale of 1-4, with 1 being no problems and 4 being safe landing not probably under these wind conditions, and (2) your rating of your own performance on a scale of A (excellent) through D (unsatisfactory). Here is a sheet showing the details of the ratings:

One, the objective difficulty of the landing:

1: No problems; minimal pilot effort required.

2: Moderate effort required; most pilots able to make a safe landing consistently with some effort.

3: Maximum pilot effort required; repeated safe landings may not be possible.

4: Controllability in question; safe landings not probable under these conditions.

Two, rate your own performance during the landing:

A. Excellent performance

B. Adequate performance

C. Marginal performance

D. Unsatisfactory performance

Any questions on the rating scales?

Again, we are testing the interface, not your pilot skills. You will be experiencing wind conditions beyond the capacity of the aircraft. Be prepared to wave off on some of the approaches. In order to help us get good results during this study, please try to imagine that it is real life, and not just a simulator. In other words, please fly the helicopter as though you were on a real mission. Try your best to land, but don't damage the helicopter! If you feel the controllability of the aircraft is in question, follow the same safety procedures you would if you were flying a real helicopter in the real world.

Do you have any questions?

A.2.2 Forms for Pilot to Fill Out

These forms were given to the pilot before we began the simulation.

1. Pilot Questionnaire – pilot name, address, and demographics (a number was written on this sheet and it was kept separately from the other information)

2. Informed Consent Form – standard consent form required by UC

3. Records Release Form – standard records release form required by UC

PILOT INFORMATION

Name: ____

Address: ____

City, State, Zip: ____

Telephone: (   ) ________ - __________ E-mail: _________________________________

Age: ______________________ Years of helicopter experience: _________________________

Total helicopter flight hours: ___________ PIC: _________ Total aircraft flight hours: ________

Helicopter flight hours last 12 months: _________________Aircraft hours last 12 mos: ________

Approx. number of shipboard landings: ____

Main types of helicopters flown: ____

____

Military or civilian? ____________________ Branch of service _________________________

Dates: ____

Main types of ships landed on (carrier, amphib, surface combatant, other) ___________________

____

Have you ever encountered any non-mechanical difficulties during a shipboard landing? ______

____

____

____

____

Are you left-handed? _______________________ Are you color-blind? ___________________

A.2.3 Order of Flight

There were four orders that the 28 approaches were presented. These were arranged and randomized as described in Chapter 5. The orders were labeled C, D, E, and F. Orders were assigned to the pilots based on the day they were flying. Here is a sample assignment page:

Orders of Flight
Pilots 4-8
Simulation Study Phase 3
July – August, 2004

Pilot Numbers 20040722, 20040723, 20040803, 20040812

20040722 - E	20040723 - F	20040803 - C	20040812 - D
20 – A2	26 – S3	47 – P5	32 – B6
21 – B5	43 – B2	33 – A7	31 – A1
35 – P4	42 – A5	34 – B3	28 – S5
38 – S7	41 – B4	27 – P7	29 – A4
23 – P1	40 – S2	36 – S1	45 – P3
24 – B7	44 – P6	37 – A6	30 – S6
25 – A3	39 – B1	22 – S4	46 – P2
46 – P2	22 – S4	39 – B1	25 – A3
30 – S6	37 – A6	44 – P6	24 – B7
45 – P3	36 – S1	40 – S2	23 – P1
29 – A4	27 – P7	41 – B4	38 – S7
28 – S5	34 – B3	42 – A5	35 – P4
31 – A1	33 – A7	43 – B2	21 – B5
32 – B6	47 – P5	26 – S3	20 – A2
47 – P5	32 – B6	20 – A2	26 – S3
33 – A7	31 – A1	21 – B5	43 – B2
34 – B3	28 – S5	35 – P4	42 – A5
27 – P7	29 – A4	38 – S7	41 – B4
36 – S1	45 – P3	23 – P1	40 – S2
37 – A6	30 – S6	24 – B7	44 – P6
22 – S4	46 – P2	25 – A3	39 – B1
39 – B1	25 – A3	46 – P2	22 – S4
44 – P6	24 – B7	30 – S6	37 – A6
40 – S2	23 – P1	45 – P3	36 – S1
41 – B4	38 – S7	29 – A4	27 – P7
42 – A5	35 – P4	28 – S5	34 – B3
43 – B2	21 – B5	31 – A1	33 – A7
26 – S3	20 – A2	32 – B6	47 – P5

A.2.4 Approach Forms

The operator had one of these forms during the simulation to take notes on. Notes were kept of the time each run began and ended, the pilot's rating of the objective difficulty of the landing, their rating of their performance during the landing, and any pilot or operator comments.

Approach Form C
Simulation Study
July – September, 2004
Fill out after each approach is completed

After each approach, I'd like you to give me two ratings:

One, the objective difficulty of the landing:
1: No problems; minimal pilot effort required.
2: Moderate effort required; most pilots able to make a safe landing consistently with some effort.
3: Maximum pilot effort required; repeated safe landings may not be possible.
4: Controllability in question; safe landings not probable under these conditions.

Two, rate your own performance during the landing:
A. Excellent performance
B. Adequate performance
C. Marginal performance
D. Unsatisfactory performance

Pilot Number ____________________

Pilot Number ______________________ Approach Form C

Scenario No/Code	Start Time	End Time	Landing Difficulty (1-4)	Pilot Perf. (A-D)	Comments
47 – P5					
33 – A7					
34 – B3					
27 – P7					
36 – S1					
37 – A6					
22 – S4					
39 – B1					
44 – P6					
40 – S2					
41 – B4					
42 – A5					
43 – B2					
26 – S3					
20 – A2					
21 – B5					
35 – P4					
38 – S7					
23 – P1					
24 – B7					
25 – A3					
46 – P2					
30 – S6					
45 – P3					
29 – A4					
28 – S5					
31 – A1					
32 – B6					

A.2.5 Post-Flight Debrief Script

Sit at the conference table. Thank them for the flight. Ask if they need anything.

Hand them the post-flight questionnaire.

Afterwards, ask some open-ended questions:

What did you think of the simulation?

What did you think of the fidelity of the simulation (how real did it seem to you, including fidelity of the displays and realism of the winds, sights, etc. encountered in the simulation)?

What are your thoughts on the use of this system for visualizing airwake?

How would you evaluate the potential of a system like this for improving shipboard safety?

Do you have suggestions for improvement to the procedures of the simulation? To the hazard visual aids?

Follow-on questions to the post-flight questionnaire:

Is there another way to display airflow motion?

Which colors for what indicator?

Did they have enough warning time?

If the airflow hazard visualization distracted them from the task of flying the aircraft, what aspects of the flight displays did the hazard indicator interfere with?

If the airflow hazard visualization blocked important visual cues, what cues were blocked?

Any other comments?

Thank them for their time, and ask them, in order to avoid biasing future subjects, to please not talk about the details of the experiment to pilots who have not flown the simulator yet. Thanks!

A.2.6 Post-Simulation Pilot Evaluation

Pilots filled out this evaluation immediately after finishing the flight simulation.

SIMULATION PILOT EVALUATION

Pilot Number ____________________

Purpose: To determine the pilot's preferences and perceptions of the visual display.
To determine the effectiveness of the display with respect to situational awareness.

Instructions: Answer the following questions on a scale of 1 - 5. 1 being strongly disagree and 5 being strongly agree.

Please read each question carefully; while two questions may appear similar, the questions have different meanings.

Please answer each question based on your overall recollection of the approaches that displayed airflow hazard indicators. Answer each question based on the following scale by circling the number that corresponds with your rating of that item.

Strongly Disagree	Disagree	Neither Agree Nor Disagree	Agree	Strongly Agree
1	2	3	4	5

1) There was sufficient information presented to warn of an impending airflow hazard encounter.
1 2 3 4 5

2) It was easy to determine the location of the airflow hazard.
1 2 3 4 5

3) The meaning of the color of the airflow hazard was clear to me.
1 2 3 4 5

4) I would be more cautious if I saw a yellow airflow hazard in my approach path.
1 2 3 4 5

5) I would wave off if I saw a red airflow hazard in my approach path.
1 2 3 4 5

6) The airflow hazard visualization distracted me from the task of flying the aircraft.
1 2 3 4 5

7) The display seemed cluttered due to the presence of the airflow hazard visualization.
1 2 3 4 5

8) The airflow hazard visualization blocked important visual cues.
1 2 3 4 5

9) The airflow hazard indicator should look like what it represents (vortex, downdraft, etc)..
1 2 3 4 5

10) It is important to me to be able to turn off the hazard visualization system at any time.
1 2 3 4 5

11) The shape of the airflow hazard was overly simplistic and did not present enough information.

12) I would have preferred more than two colors for the hazard indicators.

1 2 3 4 5

13) It would be helpful if the hazard indicator moved to display airflow motion.

1 2 3 4 5

14) It would be distracting if the hazard indicator showed airflow motion.

1 2 3 4 5

15) If I know ahead of time that a certain symbol represents an airflow hazard, then it is NOT important to me that the representation actually looks like an airflow hazard.

1 2 3 4 5

16) Overall, it was as easy to fly the simulator with the hazard indicators turned on as it was with them off.

1 2 3 4 5

17) Over time, the display became easier to fly because my experience on the simulator increased.

1 2 3 4 5

18) The presence of the hazard indicators gave me more confidence as to the state of the winds and airwake on deck.

1 2 3 4 5

19) I learned something about the location and effect of hazardous airwake on the deck of a ship by seeing the hazard indicators.

1 2 3 4 5

20) I would recommend the use of this display as a training tool for pilots.

1 2 3 4 5

21) I would use this display system if it were available on my aircraft.

1 2 3 4 5

22) Other comments?

A.3 Pilot Comments on ART Flight Simulator Quality

Pilot commentary on the fidelity and realism of Advanced Rotorcraft Technology's helicopter flight simulator was highly favorable. During the post-flight debrief, the study pilots were asked their opinions of the quality of the simulation itself, as opposed to the visual interface. One pilot commented, "The simulation was good... in the [simulator] we use, as soon as you get off the ground, you punch the autopilot." Another said, "[This simulator] is as good as any I've flown." And one said, "It's an order of magnitude better than any others I have experience with." However, suggestions for improvement were specifically elicited in the study post-flight script, and many pilots had feedback to offer.

Below are included the suggestions the pilots made for improvement to the simulation or the H-60 aircraft model.

Early in the simulation the torque meter was calibrated incorrectly, and pilots commented about that, but said it did not affect their flying. "I just ignored the torque meter." However, two pilots wished that the torque meter would be closer and not so far off to the left. On the other hand, one pilot said it didn't matter because in an actual H-60 helicopter many instruments were farther away.

One pilot wished for more sensory information. "I can't hear translational lift [an aerodynamic phenomenon important to helicopter landing performance], and many visual cues are missing... [such as might be seen in a] chin bubble [a low window through which the helicopter pilot can look down and see the ground]." Another, however, stated that, "I could feel the winds and turbulence – it was pretty realistic." One pilot complained, though, that "the flashing of the ship markings was very distracting."

One pilot with extensive UH-60 experience made a number of suggestions for improvement to the aircraft model itself. He stated that the collective was too stiff compared to the real aircraft, which made it more difficult to make small inputs. He felt the simulator had a "pitch oscillation at certain speeds," and was "more squirrelly in yaw and roll" than an actual H-60. Also, the pilot eye level in the simulator visuals appeared to be about five feet too high. (We later measured the pilot's eye level in NASA Ames's H-60, and it was approximately six feet, whereas the simulator eye level appeared to be at ten to twelve feet above the deck when the simulated helicopter was parked on the deck.) Finally, he mentioned that "the turn and ball instrument was inoperative," and that "all equipment on the ship should be yellow."

Another commented that "it was hard to slow [the simulated helicopter] down. 15 degrees pitch up should do it, but didn't." He complained about the lack of depth perception – "it's hard to judge your height over the boat." Finally, he wanted "control feedback for transverse flow... [and] stick shake for burble."

One pilot noticed that the radar altimeter did not detect the ship; when he flew over the ship deck, it still indicated altitude above mean sea level (MSL) rather than the actual height above the deck. "But the feel of the simulator itself is excellent."

One pilot commented, "the pedals feel like the pedals in a light helicopter – no heading hold or turn coordination." This pilot also found the collective stiff. And, "the turn ball needs to be operative." But, "in general, the system is good."

One pilot said, “There’s not enough force feedback on the stick in pitch, but it’s fine in roll.”

A pilot with all tandem rotor experience (CH-46) commented that all the controls seemed stiff, “but then I use pedals less than a tail rotor guy.” He also said, “the simulation is good overall.”

Most of the pilots said they enjoyed flying the simulation, and appreciated the realism of the winds and aircraft model in the simulator.

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