Copyright Warning & Restrictions

The copyright law of the United States (Title 17, United States Code) governs the making of photocopies or other reproductions of copyrighted material.

Under certain conditions specified in the law, libraries and archives are authorized to furnish a photocopy or other reproduction. One of these specified conditions is that the photocopy or reproduction is not to be "used for any purpose other than private study, scholarship, or research." If a, user makes a request for, or later uses, a photocopy or reproduction for purposes in excess of "fair use" that user may be liable for copyright infringement,

This institution reserves the right to refuse to accept a copying order if, in its judgment, fulfillment of the order would involve violation of copyright law.

Please Note: The author retains the copyright while the New Jersey Institute of Technology reserves the right to distribute this thesis or dissertation

Printing note: If you do not wish to print this page, then select "Pages from: first page # to: last page #" on the print dialog screen

The Van Houten library has removed some of the personal information and all signatures from the approval page and biographical sketches of theses and dissertations in order to protect the identity of NJIT graduates and faculty.

ABSTRACT

taux: A SYSTEM FOR EVALUATING SOUND FEEDBACK IN NAVIGATIONAL TASKS

by
Robert J. Lutz

This thesis presents the design and development of an evaluation system for generating audio displays that provide feedback to persons performing navigation tasks. It first develops the need for such a system by describing existing wayfinding solutions, investigating new electronic location-based methods that have the potential of changing these solutions and examining research conducted on relevant audio information representation techniques. An evaluation system that supports the manipulation of two basic classes of audio display is then described. Based on prior work on wayfinding with audio display, research questions are developed that investigate the viability of different audio displays. These are used to generate hypotheses and develop an experiment which evaluates four variations of audio display for wayfinding. Questions are also formulated that evaluate a baseline condition that utilizes visual feedback. An experiment which tests these hypotheses on sighted users is then described. Results from the experiment suggest that spatial audio combined with spoken hints is the best approach of the approaches comparing spatial audio. The test experiment results also suggest that muting a varying audio signal when a subject is on course did not improve performance. The system and method are then refined. A second experiment is conducted with improved displays and an improved experiment methodology. After adding blindfolds for sighted subjects

and increasing the difficulty of navigation tasks by reducing the arrival radius, similar comparisons were observed. Overall, the two experiments demonstrate the viability of the prototyping tool for testing and refining multiple different audio display combinations for navigational tasks. The detailed contributions of this work and future research opportunities conclude this thesis.

taux: A SYSTEM FOR EVALUATING SOUND FEEDBACK IN NAVIGATIONAL TASKS

by
Robert J. Lutz

A Dissertation
Submitted to the Faculty of
New Jersey Institute of Technology
in Partial Fulfillment of the Requirements for the Degree of
Doctor of Philosophy in Information Systems

Department of Information Systems

January 2008

Copyright © 2008 by Robert J. Lutz

ALL RIGHTS RESERVED

APPROVAL PAGE

taux: A SYSTEM FOR EVALUATING SOUND FEEDBACK IN NAVIGATIONAL TASKS

Robert J. Lutz

12/03/2007

Dr. Marilyn Tremaine, Dissertation Advisor — Date
Professor of Information Systems, NJIT

12-3-07

Dr. Brian Amento, Committee Member — Date
Research Professor of Information Systems, NJIT and
Principal Technical Staff Member at AT&T Labs - Research, Florham Park, NJ

12/3/07

Dr. Aries Arditi, Committee Member — Date
Senior Fellow in Vision Science, Lighthouse International, New York, NY

12\3\07

Dr. Katia Passerini, Committee Member — Date
Assistant Professor of Management Information Systems, School of Management, Joint Appointment in Information Systems, NJIT

12/3/07

Dr. Julian Scher, Committee Member — Date
Associate Professor of Information Systems, NJIT

BIOGRAPHICAL SKETCH

Author: Robert J. Lutz

Degree: Doctor of Philosophy

Date: January 2008

Undergraduate and Graduate Education:

- Doctor of Philosophy in Information Systems,
  New Jersey Institute of Technology, Newark, NJ, 2008

- Master of Business Administration,
  Rutgers University, Newark, NJ, 2000

- Bachelor of Mechanical Engineering,
  Villanova University, Villanova, PA, 1983

Major: Information Systems

Presentations and Publications:

Chen, X.C., Tremaine, M., Chun, J, Lutz, R.J., & Lacsina, P.O. (2006). AudioBrowser: A Mobile Browsable Information Access for the Visually Impaired, *Universal Access in the Information Society*, 5(1), 4-22, Springer.

To
LeeAnne, Alton, Maighread, Aoife,
Roberta and Richard

ACKNOWLEDGMENT

I would like to express my sincere gratitude to Dr. Marilyn Tremaine, who not only served as my research advisor, providing valuable and countless resources, insight, and intuition, but also constantly gave me support, encouragement, and reassurance. Special thanks are given to Dr. Brian Amento, Dr. Aries Arditi, Dr. Katia Passerini and Dr. Julian Scher for actively participating in my committee.

I am also grateful to my children (Alton, Maighread and Aoife) who lived this journey with me over the past seven and a half years. I am especially grateful to my wife LeeAnne for being my partner, confidant and support structure during this endeavor.

I am grateful to the following people and groups for their support:

- Cepstral (http://www.cepstral.com),
  Sun Microsystems (http://www.sun.com) and
  CAD Schroer (http://www.cad-schroer.com)
  for their generous donations of software technology
- My managers at Sun Microsystems, who always 'understood':
  Jim Parkinson, Roger Day, Kevin Clarke, Barry Williams, Matt Flippen, Louise Bruno and Ari Shamash.
- All of the people who volunteered as subjects and selflessly gave me their time
- My late friend John Visicaro, who inspired me
- Maighread Lutz, my photographer
- Alton Lutz, my first brave (and patient!) subject
- My friends and acquaintances in the Lions Club, National Federation of the Blind of New Jersey, New Jersey Commission for the Blind and Rutgers University. More specifically, Don Wussler, Joe Ruffalo, Marshall Klein, Eddie Montanez and Rick Gaine.

TABLE OF CONTENTS

Chapter **Page**

1 INTRODUCTION 1

1.1 Background 1

1.2 Motivation 2

1.3 The Research 2

1.4 The Layout of This Thesis 2

2 LITERATURE REVIEW 4

2.1 Introduction 4

2.2 The Nature of the Problem 5

2.3 Technology Landscape 6

2.3.1 Location Sensing 7

2.3.2 Input and Output 10

2.3.3 Mobile Devices 12

2.3.4 Networking Infrastructure 13

2.3.5 Geographical Information Systems (GIS) 13

2.3.6 General Observations and Technology Developments 14

2.4 Wayfinding for the Sighted 15

2.4.1 Definitions and Concepts 16

2.4.2 Strategies 17

2.4.3 Design Considerations 18

TABLE OF CONTENTS
(Continued)

Chapter **Page**

2.5 Wayfinding for the Blind 20
    2.5.1 Blind Wayfinding 21
    2.5.2 Occupation Aspects of Wayfinding: Orientation and Mobility 22
    2.5.3 Technological Aspects: Assistive Technology for Wayfinding 22
2.6 Technology Adaptations for User Interfaces Using Non-Visual Senses 29
    2.6.1 Sensory Substitution 29
    2.6.2 Auditory Interfaces 31
    2.6.3 Auditory Displays 32
    2.6.4 Speech 32
    2.6.5 Sonification 33
    2.6.6 Earcons 34
    2.6.7 Auditory Icons 36
    2.6.8 Hearcons 36
    2.6.9 Audition and Touch in Spatial Interpretation 37
    2.6.10 Audio Interfaces and Augmented Reality 42
2.7 Existing Systems and Opportunities for Improvements 43
    2.7.1 Research Systems 44
    2.7.2 Commercial Systems 51
    2.7.3 Comparison of System Features 54
2.8 Evaluation Methods 56

TABLE OF CONTENTS
(Continued)

Chapter **Page**

2.9 Summary of the Literature Review 57

3 DESCRIPTION OF THE TAUX SYSTEM 59

3.1 Overview 59

3.2 Illustrative Example 61

3.3 A Closer Look at the Illustration 63

3.4 A Simplified Illustration 64

3.5 Requirements 65

3.6 Solutions Survey and Analysis 67

3.6.1 Location Sensing Subsystem 67

3.6.2 GIS Subsystem 71

3.6.3 User Interface Subsystem 75

3.6.4 botGuide Subsystem 79

3.7 The Simplified Illustration, Revisited 79

3.8 Problems Solved 83

3.8.1 Experience 83

3.8.2 Tools / Libraries 83

3.8.3 Experiment 85

3.9 Basic System Operation 87

3.10 Detailed System Description 95

3.10.1 Use Case View 96

TABLE OF CONTENTS
(Continued)

Chapter **Page**

3.10.2 Process View 98

3.10.3 Development View 115

3.10.4 Logical View 134

3.10.5 Physical View 145

3.11 Advanced System Operation and Extension 149

3.11.1 Creating the New Display Class 149

3.11.2 Adding the Process Start/Stop Methods 151

3.11.3 Adding the Stop / Start / Configure Controls 152

4 INVESTIGATING THE VIABILITY OF TAUX 154

4.1 Introduction 154

4.2 Constructing the Experiment 156

4.3 Auditory Displays for Evaluation 160

4.3.1 Spatialized Audio (A1) 160

4.3.2 Spatialized Audio with Hints (A2) 161

4.3.3 Spatialized Audio with Visual Feedback (A0) 161

4.3.4 Varying Pitch (B1) 162

4.3.5 Varying Pitch, using Silence for On-Course Performance (B2) 162

4.4 Experiment Method 162

4.4.1 Independent Variables 163

4.4.2 Dependent Variables 165

TABLE OF CONTENTS
(Continued)

Chapter **Page**

4.4.3 Apparatus 171

4.4.4 Participants 172

4.4.5 Subject Demographics for Pilot Study 174

4.4.6 Procedure 175

5 RESULTS OF THE TEST EXPERIMENT 177

5.1 Subjects' Path Data 177

5.2 Descriptive Statistics 180

5.2.1 Description of Terms 181

5.3 Inferential Statistics 184

5.3.1 Correlation and Effect Size 184

5.3.2 Normality 186

5.4 Analysis of Learning Data 189

5.5 Survey Results 192

5.6 Chapter Summary 196

6 DISCUSSION OF RESULTS FROM THE TEST EXPERIMENT 197

6.1 Research Questions 197

6.1.1 Does the System Perform? 197

6.1.2 How Do the Audio Displays Compare? 198

6.2 General Observations 200

6.3 Limitations 201

Chapter Page

6.3.1 External Validity 202

6.3.2 Internal Validity 202

6.3.3 Construct Validity 203

6.4 Issues Encountered 204

6.4.1 Learning 205

6.4.2 Route Geometry 206

6.5 Proposed Improvements 206

6.5.1 Near Term 207

6.5.2 Long Term 207

7 RESULTS FROM THE FINAL EXPERIMENT 209

7.1 Revisions from Pilot 210

7.2 Data Collected and Analysis of Data 212

7.2.1 Subjects' Path Data 213

7.2.2 Descriptive Statistics for the Performance Data 216

7.2.3 Inferential Statistics for the Performance Data 218

7.3 Subject Survey Results 223

8 DISCUSSION OF RESULTS FROM FINAL EXPERIMENT 228

8.1 Discussion of Results 228

8.2 Research Questions 228

8.2.1 Did the System Perform? 229

TABLE OF CONTENTS
(Continued)

Chapter **Page**

8.2.2 How Did the Audio Displays Compare? ... 230

8.2.3 Comparison of All Performance Measures Between B2 and B1 ... 230

8.2.4 Comparison of AvgHE from Any Condition to the A0 Condition ... 230

8.2.5 DistRatio Comparison Between A2 and A0. ... 231

8.2.6 Time Measurement (TimePerUnitDistPerWP) Between A1 and A2. ... 231

8.3 Problems with the Final Test Experiment ... 232

8.3.1 Basic System Function ... 232

8.3.2 Design of the Experiment ... 235

8.3.3 Research Methods ... 237

8.4 Summary ... 237

9 CONCLUSION ... 239

9.1 Summary ... 239

9.2 Audio Feedback Design Recommendations ... 240

9.2.1 Observations About Navigation Events ... 240

9.2.2 Observations About Audio Feedback ... 243

9.2.3 Overall Recommendations ... 244

9.3 Limitations of this Research ... 245

9.4 Future Research ... 246

9.4.1 More Work with Learning Assessment ... 246

9.4.2 Consideration of Valuable Subject Suggestions ... 246

9.4.3 Full Scale Implementation ... 247

TABLE OF CONTENTS
(Continued)

Chapter **Page**

9.4.4 Modify the Apparatus 247

9.4.5 Extend the Event Model and Exploration of Hybrid Sound Models 247

9.4.6 Add and Evaluate a Driving Lane Model 248

9.4.7 Improve Measures 248

9.4.8 Study the Effects of Poor Precision on Navigation 249

9.5 Contributions 249

APPENDIX A INTERVIEWER RECORD SHEET 252

APPENDIX B IRB APPLICATION 257

APPENDIX C CONSENT FORM 263

APPENDIX D SUBJECT ADVERTISEMENT 269

APPENDIX E STUDY INTRODUCTION 271

APPENDIX F STUDY INSTRUCTIONS 273

APPENDIX G BACKGROUND QUESTIONNAIRE FOR SIGHTED USERS 285

APPENDIX H BACKGROUND QUESTIONNAIRE FOR VISUALLY IMPAIRED USERS 288

APPENDIX I POST QUESTIONNAIRE 292

APPENDIX J DEBRIEFING SHEET 296

APPENDIX K PROTOCOL FOR VISUAL ACUITY TEST 298

APPENDIX L INVESTIGATOR'S PREPARATION CHECKLIST 300

APPENDIX M SAMPLE COMMA SEPARATED TEXT FILE 302

APPENDIX N R SOURCE FILES 304

TABLE OF CONTENTS
(Continued)

Chapter **Page**

APPENDIX O USE CASE DESCRIPTIONS 310

APPENDIX P SUBJECT TRACKING PLOTS FROM TEST EXPERIMENT............ 317

APPENDIX Q SUBJECT OFF TARGET ERROR AND HEADING ERROR DATA PLOTS 323

APPENDIX R SUBJECT TRACKING PLOTS FROM FINAL EXPERIMENT......... 329

APPENDIX S METHOD DESCRIPTION FOR ANALYSIS OF RANK ORDERED SELECTIONS.. 335

REFERENCES 340

LIST OF TABLES

Table **Page**

2.1 Location Sensing Technologies 8

2.2 "35 Ways To Find Your Location" Presentation 9

2.3 Blind User Navigation Systems 55

3.1 System's 'shall' Requirements 66

3.2 System's 'should' Requirements 67

3.3 Software Components and Revision Levels 120

3.4 Coordinate Systems and Their Attributes 122

3.5 Description of Hardware Components 146

3.6 Software Library Dependencies 147

4.1 Research Questions 158

4.2 Research Hypotheses 159

4.3 Independent Variable 163

4.4 Experiment Constraints 164

4.5 Dependent Variables 171

5.1 Descriptive Statistics for Dependent Variables in Audio Feedback Experiment 182

5.2 Description of Plotted Values 183

5.3 Pearson Product-Moment Correlation Coefficients Between Dependent Variables 185

LIST OF TABLES
(Continued)

Table **Page**

5.4 Effect Size of Dependent Variables 186

5.5 Summary of Probabilities, Tabulated by Condition and Dependent Variable, for ShapiroWilk Statistic. Values Significant at the 95% Level are Marked in Bold. 186

5.6 Paired Comparisons Using Mann Whitney Statistic. Values Displayed are U Statistic and Corresponding Probability (p), with Significant Values Shown in Bold at 95% Level. 187

5.7 Support/Unsupported Status of Test Experiment Performance Hypotheses... 188

5.8 Descriptive and Inferential Statistics for Qualitative Data Collected 193

5.9 Comparison of Means of User Preferences for Display Modes 195

5.10 Hypotheses and Reject/Support Status for User Preferences 196

7.1 Ordering Utilized for Latin Squares Design 211

7.2 Descriptive Statistics for Final Experiment 217

7.3 Pearsons Product-Moment Correlation Coefficients Between Dependent Variables for Final Experiment 219

7.4 Summary of Probabilities, Tabulated by Condition and Dependent Variable, for Shapiro-Wilk Statistic 220

7.5 Paired Comparisons Using Mann Whitney Statistic. Values displayed are U Statistic and Corresponding Probability (p), with Significant Values Shown in Bold at 95% Level 221

7.6 Supported/Unsupported Status for Performance Hypotheses During the Final Experiment 222

LIST OF TABLES
(Continued)

Table **Page**

7.7 Descriptive and Inferential Statistics for Attitudes and Beliefs Data Collected 226

7.8 Comparison of Means of User Preferences for Display Modes in Final Experiment 226

7.9 Hypotheses and Supported/Unsupported Status for User Preferences 227

O.1 Pre-Experiment Verification Use Case 311

O.2 Training Use Case 312

O.3 Navigate Route Use Case 313

O.4 Export Data Use Case 314

O.5 Configure Sound Feedback Use Case 315

O.6 Develop New Audio Feedback Mechanism Use Case 316

LIST OF FIGURES

Figure **Page**

2.1 Personal guidance system - early days. 46

2.2 Personal guidance system in 1993. 47

2.3 Humanware system. 52

2.4 Illustration of user navigation. 53

2.5 Arrival at destination. 54

3.1 Ben's navigation. 61

3.2 Navigation path in Medusa 2D CAD system. 73

3.3 2D navigation path in evaluation system. 74

3.4 taux evaluation system as viewed from graphical user interface. 78

3.5 Investigator (left) views the evaluation system console while subject (right) follows the experimental protocol using the tablet and puck device. 80

3.6 Investigator's console, showing subject's progress. 82

3.7 Directory structure for route data. 88

3.8 Contents of directory with route data for a condition. 89

3.9 Path tab on evaluation system console. 89

3.10 I/O tab of the evaluation system. 90

3.11 'Train' tab within taux evaluation system. 91

3.12 Adding an investigator's note during a trial. 93

3.13 Exporting trial data. 94

3.14 Philipe Kruchten's 4+1 view model of software architecture. 96

LIST OF FIGURES
(Continued)

Figure **Page**

3.15 Kruchten's 4+1, the use case view. 96

3.16 Evaluation system use case diagram. 97

3.17 Kruchten's 4+1: process view. 98

3.18 Main process activity diagram. 99

3.19 Services startup activity diagram. 101

3.20 TabletProcessor activity diagram. 103

3.21 AnnouncerDisplay activity diagram. 104

3.22 JOALDisplay activity diagram. 106

3.23 TalkingGuideDisplay activity diagram. 108

3.24 MidiDisplay activity diagram. 109

3.25 Heading error. 110

3.26 Investigator's screen showing investigator controls and map area navigational status. 112

3.27 GraphicalDisplay activity diagram. 113

3.28 Data sampler activity diagram. 114

3.29 Kruchten's 4+1 model - development view 115

3.30 Component diagram. 118

3.31 Testing: navigating from the screen. 129

3.32 Logging output. 130

3.33 Exporting data from experiment. 132

LIST OF FIGURES
(Continued)

Figure **Page**

3.34 Experiment CSV data viewed in spreadsheet program.................................... 133

3.35 Krutchen's 4+1 model - logical view. 134

3.36 NavigationManager class diagram.. 136

3.37 AnnouncerDisplay class diagram... 135

3.38 TabletProcessor class diagram. 137

3.39 Jwintab class diagram. 138

3.40 MainJFrame class diagram. Non-essential private operations and attributes are suppressed for legibility. 139

3.41 Waypoint class diagram.. 141

3.42 TravelerRoute class diagram.. 141

3.43 TrialData class diagram.. 143

3.44 LocationObservation class diagram. 144

3.45 TrackDataList class diagram.. 144

3.46 Sampler class diagram... 145

3.47 Kruchten's 4+1 physical view. 145

3.48 System components diagram.. 146

4.1 Subject navigating along a trivial path.. 166

4.2 Subject completing trivial navigation. 167

4.3 Illustrating planar veer. 169

4.4 Illustrating angular veer. 170

LIST OF FIGURES
(Continued)

Figure **Page**

5.1 Subject navigating in condition A1. While not optimal performance, this subject was able to perform the task. 179

5.2 Subject navigating in condition A2. This is the same subject that was shown inFigure 5.1. Note that the navigation is improved in this condition. 179

5.3 Summary plots for descriptive statistics of dependent variables. 184

5.4 Example OTE and HE trends for a subject during one condition. 191

5.5 Subjects responses about preferences. 195

7.1 Traversals of two subjects in trial 2 of condition A1. 214

7.2 Traversals of two subjects in trial 2 of condition A2. 214

7.3 Summary plots for descriptive statistics of dependent variables. 218

7.4 Subject responses about preferences for final experiment. 225

P.1 Subject route data for condition A0. 318

P.2 Subject route data for condition A1. 319

P.3 Subject route data for condition A2. 320

P.4 Subject route rata for condition B1. 321

P.5 Subject route data for condition B2. 322

Q.1 OTE and HE trends for all subjects – group - A0. 324

Q.2 OTE and HE trends for all subjects group - A1. 325

Q.3 OTE and HE trends for all subjects group – A2. 326

Q.4 OTE and HE trends for all subjects group – B1. 327

LIST OF FIGURES
(Continued)

Figure **Page**

Q.5 OTE and HE trends for all subjects group – B2. 328

R.1 Subject route data for condition A0. 330

R.2 Subject route data for condition A1. 331

R.3 Subject route data for condition A2. 332

R.4 Subject route data for condition B1. 333

R.5 Subject route data for condition B2. 334

CHAPTER 1

INTRODUCTION

1.1 Background

Humans, being sighted, visually impaired or blind, need to navigate throughout our environment. These navigators, also known as *wayfinders*, need to access contemporary information necessary for the *wayfinding* task. This access needs to be as quick, efficient and effortless as possible. Sighted wayfinders utilize much of the information needed visually, where their visually impaired counterparts suffer a deficit due to the absence of this rich information resource. Several trends suggest action is necessary to address a growing problem. Visual impairment and blindness rates are increasing, as the baby boomer generation approaches retirement age and suffer the health effects associated with age. The technological capabilities to access information are also increasing; capabilities that can expose environmental information in new and different ways. A challenge exists and an opportunity is presented to combine emerging capability with an increasing need.

> Human wayfinding, considered from the perspective of visually impaired and blind pedestrian navigators, consists of two distinct components: sensing the immediate environment for impediments to travel (e.g., obstacles and hazards) and navigating to remote destinations beyond the immediate perceptible environment (Loomis, 1998).

This works aims to provide technology that helps the visually impaired or blind pedestrian acquire remote destinations similar to the way the long cane and dog guide aid with hazard avoidance.

1.2 Motivation

There is a population of people who through their disability become unable to normally access the environment we all share. In the U.S., 11.4 million people experience vision loss with ten percent of those considered legally blind. These numbers are expected to double by 2010 (Ross & Lighten, 2005). It would be useful to develop technology that supports mobility and autonomy for such individuals. This thesis focuses on developing such technology for blind and visually impaired individuals. In this work a unique problem is addressed, that of a visually impaired pedestrian navigating a large physical environment, e.g., a building floor or a neighborhood.

1.3 The Research

This research does the following. First, a literature review is conducted to survey the available technology and related research. It is found that significant technology advancements in related areas are present and many research developments in auditory display are yet to be applied to wayfinding. Some opportunities to improve the state of the art for assisted wayfinding are identified. Next, a system is proposed that allows for the construction and evaluation of candidate improvements. Finally, several proposed display improvements are defined and evaluated.

1.4 The Layout of this Thesis

This thesis is presented as follows. Chapter 1 is this introduction. In Chapter 2, the results of the literature review are presented.

Next, building on the findings and conclusion of Chapter 2, an evaluation system is proposed in Chapter 3. With a perceived weakness identified in existing wayfinding systems, a system is proposed that allows for alternate design implementations which provide real time audio-based guidance to the subjects performing navigational tasks. The system provides the ability to construct and evaluate such alternatives. The proposed system is fully described using an established methodology and artifacts, following a traditional Unified Modeling Language (UML) approach.

Chapter 4 begins by summarizing the research questions considered for study. These are subdivided into two major areas. The first area considers the taux evaluation system; whether it is effective at modeling and evaluating navigational tasks. The second looks at candidate audio display methods, and compares these based on proposed hypotheses. Chapter 4 then describes the methods selected for experimentation.

Chapters 5 and 6 present pilot study results and a discussion, respectively. Chapter 7 provides the results of the final experiment. Chapter 8 discusses the results presented in Chapter 7.. Chapter 9 provides a closing discussion that contains several different components. These are a summary of the work completed, audio feedback design recommendations, limitations of the research, future research and contributions.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

These review contains several sections. Initially, a description of the growing vision impairment problem is provided. This is done, in part, to characterize the user population requiring technology support who will primarily be senior citizens. In the next section, an update of current technology trends is explored, with the focus on demonstrating what capabilities are now found in tools and applications that could be adapted to support wayfinding for blind users. This section is followed by a discussion of how sighted people carry out wayfinding. Next, the literature review discusses what is known about how visually impaired and blind people wayfind within their physical environment. This information is given to provide insights into potential designs. The next three sections switch focus, primarily considering research literature and secondarily considering commercial solution information. Section 5 explores a variety of user interfaces that have been researched that utilize sound as an output modality by applications for blind users. This background is provided since sound has been shown to be an effective display mechanism for information, and because sound is often substituted for missing visual information by blind users. Section 6 identifies navigation systems that have been developed for blind wayfinders. It considers underlying technologies, features, and a comparison of the systems. Section 7 provides a survey of methods and measures that have been employed to evaluate the capabilities of various navigational systems. These methods and measures will be utilized later in this work. Finally, a summary is provided.

2.2 Nature of the Problem

There are approximately 11.4 million people in the US who experience vision loss ranging from mild to totally blind. Ten percent of this number, or 1.1 million people, are legally blind. By 2010, these numbers will nearly double. (Ross & Lighten, 2005).

Several characterize the epidemiology of "low vision" users. Here, low vision is defined as "a permanent visual impairment that is not correctable with glasses, contact lenses or surgical intervention and that interferes with normal everyday functioning" (Mehr, 1975). It is estimated that one percent of western countries suffer from low vision (Dowie, 1988; Strong, Pace, & Plotkin, 1988). 14 million Americans (1 in every 20) have visual impairment (Kupfer, 2000), and visual impairment affects nearly 5 million Americans to the extent that they are unable to read newsprint, even with the aid of fully refractive correction (Nelson & Dimitrova, 1993). Eight percent of Americans over 65 have low vision; this percentage jumps to 25% for those over 85. (Nelson, 1987).

The number of Americans over 65 is expected to double between 1995 and 2030 (National Advisory Eye Council, 1993). LaPlante (1988) ranks vision loss third, behind arthritis and heart disease, among conditions that cause persons older than 70 years to need assistance in activities of daily living. Given the importance of vision on independence and the growing population of low vision users, an increasing number of people are at risk of becoming dependent on others.

In order to understand what can be done to alleviate this pending problem of having a significant portion of the population requiring assistance because of vision loss, it is first necessary to review the technology that is now available that might be put into use to help the low-vision or blind individual. This is done in the next section which lays out the "technology landscape" for the reader.

2.3 Technology Landscape

Advancements in computing technology are frequently underpinned by one or more advancements in underlying technology areas. It follows that advancements with visually impaired pedestrian navigation will also rise with the progression of constituent technologies. The following discussion offers an example of a similar advancement as evidence. Next, this discussion identifies the technology areas that comprise the constituency for these systems. Some general observations about technological advancement and its applicability to this research follow.

In the early 1990s, a confluence of technological developments emerged and presented an unparalleled opportunity. These developments included: (1) the availability of sufficient desktop computing power, (2) network connectivity, and (3) standardized network services (ftp, gopher, wais, http, etc.) and provided the infrastructural foundation for today's internet. Combining these parallel developments produced results that were explosive; many high value services emerged.

In a similar way, developments in the following areas provide a digital fabric for constructing navigation systems: location sensing, mobile devices, information input / output capabilities, wireless infrastructure and graphical information system (GIS) data. The following sections will briefly describe the salient developments in the named technology areas and identify those features that are of interest to the navigation researcher.

2.3.1 Location Sensing

To provide navigation services, navigation applications need to know the physical location of people, places and things. Many mobile devices are equipped with location determination apparatus. If not, many more are easily extended to do so. Additionally, device hardware for networking (Wi-Fi, Bluetooth, Ultra-Wideband) can be adapted and utilized for location determination. Many solutions have been engineered; each has limitations specific to the problems that it solves. As a result, these solutions vary in many ways: the physical phenomena used, the form factor for sensing apparatus, the power requirements, the usage of infrastructural versus portable elements, and the resolution in time and space (Hightower & Boriello, 2001). These authors provide developers with a summarization and taxonomy to use when selecting from the available solutions.

The summary is listed as follows:

Table 2.1 Location Sensing Technologies

Technology	*Technique*	*Physical*	*Symbolic*	*Absolute*	*Relative*	*LLC*	*Recognition*	*Accuracy and Precision if available*	*Scale*	*Cost*	*Limitations*
GPS	Radio time-of-flight lateration	●		●		✓		1-5 meters (95-99 percent)	24 satellites worldwide	Expensive Infrastructure $100 receivers	Not indoors
Active Badges	Diffuse and infrared cellular proximity		●	●			✓	Room size	1 base per room, badge per base per 10 sec	Administration costs, cheap tags and bases	Sunlight and florescent light interfere with infrared
Active Bats	Ultrasound time-of-flight lateration	●		●			✓	9 cm (95 percent)	1 base per 10 square meters, 25 computations per room per sec	Administration costs, cheap tags and sensors	Require ceiling sensor grid
Motion-Star	Scene Analysis, lateration	●		●			✓	1mm, 1ms 0.1° (nearly 100 percent)	Controller per scene, 108 sensors per scene	Controlled Scenes, expensive hardware	Control unit tether, precise installation
VHF Omni Direction Raging	Angulation	●		●		✓		1° radial (≈ 100 percent)	Several transmitters per metropolitan area	Expensive infrastructure, inexpensive aircraft receivers	30 -1 40 nautical miles line of sight
Cricket	Proximity, lateration		●	○	○	✓		4 x 4 ft. regions (≈ 100 percent)	≈ 1 beacon per 16 square ft.	$10 beacons and receivers	No central management receiver computation
MSR RADAR	802.11 RF scene analysis and triangulation	●		●			✓	3-4.3m (50 percent)	3 bases per floor	802.11 network installation, ≈ $100 wireless NICs	Wireless NICs required
PinPoint 3D-iD	RF lateration	●		●			✓	1-3m	Several bases per building	Infrastructure installation, expensive hardware	Proprietary 802.11 interference
Avalanche Trans-ceiver	Radio signal strength proximity	●			●		✓	Variable 60-80 meter range	1 transceiver per person	≈ $200 per receiver	Short radio range, unwanted signal attenuation
Easy Living	Vision, triangulation		●	●			✓	Variable	3 cameras per small room	Processing power, installation cameras	Ubiquitous public cameras
Smart Floor	Physical contact proximity	●		●			✓	Spacing of pressure sensors (100 percent)	Complete sensor grid per floor	Installation of sensor grid, creation of footfall training database	Recognition may not scale to large populations
Automatic ID Systems	Proximity		●	○	○		✓	Range of sensing phenomena (RFID typically <1m)	Sensor per location	Installation, variable hardware costs	Must know sensor locations
Wireless Andrew	802.11 Proximity		●	●			✓	802.11 cell size, (≈ approx. 100m indoor, 1km free space)	Many bases per campus	802.11 deployment, ≈ $100 wireless NICs	Wireless NICs required, RF cell geometries
E911	Triangulation	●		●			✓	150-300m (95 percent)	Density of cellular infrastructure	Upgrading phone hardware or cell infrastructure	Only where cell coverage exists
SpotOn	Ad hoc lateration	●			●		✓	Depends on cluster size	Cluster at least 2 tags	$30 per tag, no infrastructure	Attenuation less accurate than time-of-flight

(Source: Hightower & Boriello, 2001)

An additional summary of location detection strategies was presented by Heathcote at the 2004 O'Reilly Emerging Technology Conference (Heathcote, 2004). The following table, summarized from the archived presentation provided, follows:

Table 2.2 Tabulated From "35 Ways to Find Your Location" Presentation

	Category		**Accuracy**
0	General	assume: The Earth	~510 square megameters
1		The time (day/night, time zone)	1000 miles
2-7		cultural clues (available cell operators, wi-fi providers, phone num syntax, avail newspapers, language being spoken)	1000 – 100,000 miles
8		Ask someone	10 meters
9		Use a map	10 meters – 1 mile
10	Mobile phone location	cell ID	50 meters – 2 miles
11		cell ID (local lookup)	50 meters – 5 miles
12		angle of arrival (AOA)	50 meters – 200 meters
13		time difference of arrival (TDOA)	30 meters – 50 meters
14		observed time difference (OTD)	25 – 250 meters
15		assisted GPS	10 meters – 50 meters
16	Geo-location technology	GPS	10 meters – 75 meters
17		WAAS and other GPS enhancements	2 meters – 25 meters
18		differential GPS	1 – 3 meters
19	Street furniture	post codes / zip codes	10 meters to ... miles
20		street names	20 meters to hundreds of miles
20a		street corners / intersections	10 meters to 5-10 miles
21		street numbers	10 -100 meters
22		business names	10 meters
23		landmarks and littlemarks	< 1 mile
24-		phone boxes / public transport stops / utility markings	10 meters
27		location street signs	10 meters
28		geowarchalking	depends
29	Emerging technology	dead reckoning	As good as initial lock
30		Wi-fi triangulation	5 – 20 meters
31		Broadcast TV/radio triangulation	50 meters
32		IP lookup	A country, a continent
33	Location advertising	encoding location in access point name / location points	100 meters.
34		local servers / Rendezvous	100 – 300 meters
35		bluetooth	1 – 100 meters
36		RFID	Dead – 50m
37	A social future	who you are near (inference)	N/A
38		objects you are near	N/A
39		The road most traveled	N/A

(Source: Source Heathcote 2004)

The previously described technology surveys offer comparative information about location technologies and capabilities to the developer or researcher. Interestingly, Heathcote (2004) aggressively predicts: '*in ten years there will be "no concept of lost."*' But, he also advises: when picking a location detection strategy, there is no magic bullet. He suggests that there is a toolbox of solutions that must be utilized based on the specific needs at hand. These technology surveys and toolboxes will be considered later as the taux evaluation system is constructed.

Two future research and development areas in location awareness are positioned to deliver added value to blind pedestrian navigators. *Sensor fusion* is the defined as the use of multiple technologies or location systems to form hierarchical and overlapping levels of sensing. *Ad hoc location sensing* employs mobile peer elements and rely on cooperation of the elements to derive both absolute and relative location. (Hightower & Boriello, 2001). Sensor fusion and ad hoc location sensing both offer a promise of low cost, highly accurate location information. As these are future capabilities and still evolving, this research will plan for but will not depend on them.

2.3.2 Input and Output

Having considered the location sensing subsystem of navigation systems, relevant developments in user interface subsystems are now considered. Whereas traditional user interface mechanisms like keyboards, mice and CRTs were not well suited to mobile pedestrians, developing mechanisms such as audio and synthetic speech are increasingly so. Audio and synthetic speech output technologies are at the center of the research being proposed. These are discussed next.

Speech processing technology has progressed significantly in recent years. Interactive voice response (IVR) systems have evolved from proprietary platforms to standardized platforms. User interaction dialogs and entire systems can be easily constructed completely via standard markup languages by dialog designers. Although this development is not directly applicable to the navigation work discussed here, the emergence of standard markup languages and user interface design practices will provide benefits.

Automated speech recognition (ASR) and rendered text-to-speech (TTS) capabilities have long existed but have been expensive, proprietary and have consumed significant computing resources. The quality of user experience for speech interfaces has lagged considerably when compared to visually based user interfaces. Recent developments indicate that these trends are shifting: open versions of ASR (CMU Sphinx, http://cmusphinx.sourceforge.net/html/cmusphinx.php) and TTS (Sun/Java FreeTTS, http://freetts.sourceforge.net/docs/index.php) now exist. Further improvements in performance and affordability are anticipated. Open source versions pressure the established vendors; prices drop as a result. Quality of the open source and commercial versions has improved. The computing needs have not reduced significantly, but processing platforms have increased in capability and can handle these user interactions much better.

Rosenfeld, Olsen and Rudnicky (2001) make an interesting prediction. For several reasons that they cite, they predict that "Only speech will scale as technology progresses." (Rosenfeld et.al, 2001, p.37). If they are correct, then speech capability, affordability and performance will only continue to increase and become more ubiquitous. And, assuming they are correct, the navigation researcher should consider speech interfaces in solutions to achieve maximum benefit.

Additional user interface devices continue to proliferate. These can be observed in portable game consoles, appliances, and cell phones. Instances include finger print readers, touch screens, pointing devices, chorded keyboards, gloves, microphones, and speakers. One related design is suggested by Amento, Hill and Terveen (2002). This device uses a wristband mounted contact microphone to permit a bio-acoustical fingertip gesture interface. This interface is capable of sensing tap, rub and flick gestures. This device, or others like it, could provide highly effective "eyes free" interface components for wayfinding solutions.

Development in speech, audio and a variety of other input/output devices offer the researcher with a variety of options that were hard to imagine a short time ago.

2.3.3 Mobile Devices

There are many options for the selection of a main platform or system for navigation. Mobile devices, in the forms of laptop computers, MP3 players, PDAs, cell phones, hybrid devices, and personal game consoles have proliferated over the past several years. On board capabilities have increased: memory, input / output capability, graphics resolution, network connectivity and throughput capability rival desktop systems from those of not that long ago. In many cases, multiple options for network connectivity are offered (Wi-Fi, UMTS, Bluetooth, EDGE, etc.) The current device portfolio provides plenty of opportunity for navigation system developers to create effective, affordable and innovative solutions.

2.3.4 Networking Infrastructure

While standalone navigation systems may be possible, tremendous value exists in networked solutions. Complementing the mobile devices' capabilities to connect to multiple networks, the installed network capability continues to grow to support these devices. Cellular carriers continue to enhance their capabilities to provide 3rd generation (3G) network capabilities such as UMTS and eVDO (Chan & Ramjee, 2005). These mobile networks offer throughput characteristics comparable to current in-home network capabilities. Schools, towns, libraries and campuses provide increasing 802.11 (WiFi) networking capabilities to their constituencies via hotspots. Wireless hotspots, both public and commercial, continue to proliferate. The continued expansion of network infrastructure presents a researcher with the opportunity to build information-rich navigation solutions for blind users.

2.3.5 Geographical Information Systems (GIS)

Similar to the pattern described in speech technologies (ASR and TTS), GIS data systems have been traditionally expensive and proprietary. With the advent of direction based systems like Mapquest (http://www.mapquest.com/), MSN/Mapblast (http://www.mapblast.com/), Yahoo Maps (http://maps.yahoo.com/) and Google Maps (http://maps.google.com/), GIS information has become much more accessible. Additionally, programmatic application interfaces provided by Google (http://www.google.com/apis/maps/) and Yahoo (http://developer.yahoo.com/maps/) make access to and utilization of

GIS capability and affordability much easier that in times past. GISs are at the heart of navigation systems, and increased capability provides a rich opportunity to the navigation researcher.

2.3.6 General Observations about Technology Developments

This section provides an observation about the nature of developments for information technology. It then offers a call to action for researchers and a prediction about the reaction of interested commercial parties.

In all of the above referenced developments, a trend is observed. Previously, solutions existed but were available through proprietary channels. As time progressed, these technologies entered the mainstream. As they do, they became available on non-proprietary platforms; they conform to industry standards and are obtained at lower price points. In some cases, these are offered free-of-charge based on open-source licensing arrangements. This pattern exists in the internet analogy presented earlier. More specifically, networked computing systems were proprietary with expensive software and the privilege of rich corporate entities. With the confluent developments, networked systems have evolved to be very standardized, very inexpensive and exposed to many consumers. The emergent system is nothing less than remarkable. The same prospect exists for navigation system and its respective components, albeit not as grand. The navigation-related developments listed provide opportunities for researchers and developers to assemble navigation applications for blind persons based on these previously, prohibitively expensive technologies.

An observation by Robert Metcalfe, who is credited as a co-inventor of Ethernet, provides context for network and information technology progress.

Metcalfe's Law states that the value of a network equals approximately the square of the number of users of the system (n^2) (Downes & Mui, 1998). New services, such as wayfinding, are facilitated by supporting technological developments and bring more users to the network. Following Metcalfe's Law, new technologies (or simply the appearance of older technologies at more affordable levels), will bring more users and continue to add value to the network. Diligent researchers have a duty to survey emerging and evolving technologies, to identify emergent opportunities. This research attempts to do this. Subsequently, astute commercial entities will determine how to monetize this value; visually impaired and blind users will benefit.

To summarize, developments in multiple technological areas have occurred which can underpin new navigation systems for visually impaired and blind users. The developments either introduce a new capability or offer a previous capability at a lower level of cost. Many of the advancements have not yet been applied to personal navigation; an opportunity exists to meet this challenge. The work of this research intends to respond, in part, to that challenge.

Having surveyed the landscape of technology components available to a developer and researcher of blind wayfinding solutions, the reader is now directed to the next section which contains a discussion of how sighted people carry out wayfinding tasks.

2.4 Wayfinding for the Sighted

In order to understand how a disabled person might perform visually impaired pedestrian navigation better, an investigation into wayfinding (for sighted users) is performed in this section. In the next section, wayfinding processes used by visually impaired users will be considered more closely. In the sections that follow, preceding technology adaptations of visually impaired user environments are surveyed.

The following section will identify key definitions, concepts, strategies and design considerations for wayfinding. It is shown that sighted people use information observed in and retrieved from their environment while wayfinding. This will provide a foundation showing that vision is an integral mechanism for sighted users, and that providing substitute information for what is provided by vision for blind wayfinders will prove beneficial.

2.4.1 Definitions and Concepts

The term *spatial orientation* has its origins in the research literature in the field of cognitive psychology. A substantial body of psychological research has developed during the past 50 years about various aspects of spatial organization, both in humans and in animals. (Rieser & Garing, 1994; Schone, 1984). Psychologists who study perception and cognition use the term spatial orientation in a relatively narrow sense to refer to knowledge of the spatial relationship (e.g., the alignment or position of one's entire body, or part of the body, to objects or locations. "Environmental psychologists and others use the term *wayfinding* to refer more broadly to the process of navigating through an environment and traveling to places by relatively direct paths." (Blasch, Wiener & Welsh, 1997, p39).

Geruschadt and Smith (2000) identify several key advantages of sight in wayfinding:

> In addition to the speed and volume of information obtained through sight, it is the distance from which the information can be

> obtained that is of ultimate importance. In a mobility context, distance means anticipation, the ability to preview the travel path... Distance as offered through vision, also permits quick and easy orientation. For example, walking into an unfamiliar building, the sighted person quickly scans the area for finding entrances and exits, office rest rooms etc. The sighted traveler utilizes an anticipatory proactive style of mobility that is characterized by quickly obtaining and processing critical information.

Applying this observation to the research at hand, it is strongly suggested that providing more useful information to a disabled person performing navigation to distant locations will improve the wayfinding process for them.

To provide additional context, a definition of *wayfinding* is offered as stated by Carpman & Grant (2006):

> Wayfinding is a fancy word for the series of things people know and do in order to get from one place or another, inside or outside. Wayfinding can be a snap or an onerous take, depending on the person, the environment, and the situation. You can think of wayfinding as a five step process. It starts with "knowing where you are." It means knowing your destination, following the best route to your destination, being able to recognize your destination, and finding your way back to your starting point.

Next, an important characterization of *wayfinding* components provided by Loomis (1998) will be important throughout the next several sections. "Human wayfinding consists of two distinct components: sensing the immediate environment for impediments to travel (e.g., obstacles and hazards) and navigating to remote destinations beyond the immediate perceptible environment."

2.4.2 Strategies

Edward Tolman (1948) performed famous experiments where rats explored for food contained within mazes. He found that, over time, the rats' completion times dropped and error rates fell. He concluded that the rats created "cognitive maps," mental representations of the spaces they navigated in. Since 2500 B.C., humans have transformed their own "cognitive maps" to symbolic presentations for the purposes of collaboration and memory. In almost all cases the symbolic maps are recorded pictorially and interpreted with the sense of vision.

Wayfinding strategies are observed in animal and human behavior. These strategies are categorized into two areas: geocentric and egocentric. Geocentric strategies employ landmarks and any available map information. Egocentric strategies employ self-aware observations of distance and direction. (Morville, 2005). While egocentric strategies may or may not utilize vision, geocentric (also called allocentric or exocentric) most probably will.

Several technology adaptations are possible that would benefit the blind traveler in both geocentric and egocentric navigation modes. For geocentric navigation, map artifacts and visual landmarks can be made available to users without vision via alternate (non-vision) displays. For egocentric wayfinding, contemporaneous reporting of progress can be used to augment the traveler's perception and memory.

2.4.3 Design Considerations

Geocentric and egocentric strategies lend themselves to both natural and man-made environments. In *The Image of the City*, Kevin Lynch (1960) reported on extensive studies and focuses on the man-made *built* environments. He inspired a generation of planners to envision urban spaces as a functioning whole. He defined the concept of *legibility* for cities. Legible cities are those where a traveler can easily construct an environmental model of the core elements and easily navigate within the environment. He suggested that proper alignment and cooperation of elements he defined (paths, edges, districts, nodes and landmarks) provide legibility. Conversely, urban spaces lacking this alignment are not legible, and contribute to frustration and anxiety. Planners have now utilized Lynch's guidance for more than four decades. Clearly, vision helps to expose legible urban elements to sighted travelers, and reduces frustration and anxiety. Affording the blind user comparable access to legible components should serve to aid the blind wayfinder.

Further advice for construction of ethical and economical *built* environments is provided by designer Paul Arthur and architect Romedi Passini (1992). They suggest that ethical considerations prevail because poorly constructed environments can result in anxiety, injury and death; poor execution many also result in lost time and unnecessary cost. They offer the following suggestions and experience:

- We always provide information in sequence. Information about the destination zones appears once the visitors have entered the building.

- On signs and maps, only a small number of written items, generally three at most, can be read at a glance.

- Subway route maps have been effective because of, and not despite, the way in which they have sacrificed reality for simplicity.

- Finally, we reiterate the importance of redundancy in wayfinding communication. The use of multiple means to communicate the same information is the best guarantee that the message gets across.

Although the practices identified by Arthur and Passini are targeted at the sighted wayfinder, these can be helpful guidance in constructing wayfinding environments and solutions for blind wayfinders.

This section discussed definitions, strategies and design considerations that influence wayfinding processes for sighted individuals. Suggestions are provided that indicate how these concepts, exposed via technology, could benefit visually disabled persons performing pedestrian navigation. The next section will expand on this foundation and consider what is known about how blind users find their way in their physical environment.

2.5 Wayfinding for the Blind

The previous section considered the process of wayfinding, in a general sense. This section expands on that foundation and considers the process from the perspective of a visually impaired traveler. Again, a pedestrian, or the visually impaired pedestrian navigation process, is the central focus. This section provides several refinements to the general discussion: the conceptual, occupational and technological aspects of wayfinding of visually impaired travelers.

Blind users need information about the environment to aid in their wayfinding activities. Recall Loomis' characterization, where wayfinding is divided into two areas: obstacle avoidance and acquisition of navigation information to reach distant destinations. These categories are the same for sighted or unsighted navigation, but benefit from closer inspection in the case of visual impairment or blindness. With sighted users, much of obstacle avoidance may be taken for granted as sighted travelers easily avoid hazards such as curbs, low hanging branches, stairs or open manhole covers. With destination acquisition, similar arguments apply. Now consider low vision users; occupational and technological solutions for obstacle avoidance are mature and well understood. Much of the technology employed is "low technology" and has been in use for an extended period of time (long cane, guide dogs, etc.). Additionally, many of the existing solutions and practice apply to nearer range obstacle avoidance, rather than farther range destination acquisition. Opportunities for introduction of newer, low cost, "higher technology" augmentations for destination acquisition will follow. But before exploring existing occupational and technological approaches, a brief conceptual overview is provided.

2.5.1 Blind Wayfinding

Blind users use perceptual and cognitive components when wayfinding. Perceptual sensors include touch, smell, proprioception and hearing. Proprioception is the perception by an animal of stimuli relating to its own position, posture, equilibrium, or internal condition. Cognitive components include memory, cognitive maps and spatial updating (Blasch, Wiener & Welsh, 1997, p. 46). Spatial updating can also be referred to path integration, dead reckoning and inertial navigation (Blasch, Wiener & Welsh, 1997, p. 31). Recall, from the previous section, that all wayfinders use both geocentric and egocentric strategies to wayfind. Blind wayfinders use their proprioceptive processing and spatial updating capabilities to perform egocentric wayfinding, while using memory and cognitive maps to perform geocentric wayfinding. As was previously suggested, technology adaptations can be considered to improve geocentric and egocentric navigation approaches.

2.5.2 Occupational Aspect of Wayfinding: Orientation and Mobility

Orientation and Mobility (O&M) is a label applied to the professional practice that help visually impaired and blind users learn to safely travel. This profession grew out of work done following World War II. Modern work was initiated by Dr. Richard Hoover at the Valley Forge Army Hospital; subsequent work was transformed and continued within the U.S.'s Universities. Although this work began in the 1940's the term *Orientation and Mobility* was not in wide spread usage until the 1950's. Up until that time, the term *foot travel* was used.

O&M considers several areas that provide the base knowledge for practitioners. These are: the Human Systems, the Mobility Systems and Learning. Human systems consider perception, conceptualization of space, hearing, mechanics of bodily movement and psychosocial factors. Mobility systems consider tools, materials and environmental features that aid the independent traveler. Finally, learning concepts are studied and applied to specific students using the base knowledge from the human system and mobility systems category.

With occupational training, practitioners help visually impaired and blind users learn the base knowledge required to safely travel.

2.5.3 Technological Aspects: Assistive Technology for Wayfinding

This section provides a survey of technological offerings that provide assistance to disabled persons performing navigational tasks. This survey considers both low tech and high tech offerings, for both obstacle avoidance and destination acquisition.

2.5.3.1 Dog Guides. Dogs are are specially trained and paired with visually disabled people. Referring to Loomis' prior definition of the primary components of human wayfinding, dog guides are applied primarily to navigation of immediate environment features and only secondarily to remote destinations that are beyond immediate perception. Dog guides respond to specific voice and hand signals. In an urban setting, the dog will respond to commands such as "forward", "left" or "right." They will proceed until they reach the end of a block or other obstacles are encountered. The blind user, or *handler*, maintains the responsibility to navigate to the desired destination, maintain alignment and to provide the primary decisions for street crossings. (Blasch, Wiener & Welsh, 1997 p.261-262).

More detail about dog guides follows for contextual purposes. The following paragraphs briefly discuss the history of dog guides, adoption rates of dog guides and specific difficulties that are encountered with the utilization of guide dogs.

Guide dogs have been utilized for a long period of time. Pictorial images of dog guides date back to ancient civilizations. Specific details of usage in those times are mostly unknown; systematic training was not known to be performed until after the World War I. Dog guides were trained after WWI in France and Germany for blinded war veterans. In 1929 the first U.S. dog guide school, The Seeing Eye, was founded in Nashville, Tennessee. As of 1994, at least ten dog guide schools were known to be in operation (Blasch, Wiener & Welsh, 1997, p260, p570).

Adoption rates for dog guides are low. As recently as 1997, Blasch, Wiener & Welsh cite an older study finding only 1-2% adoption of dog guides by blind users (this references a 1960 study by Finestone, Luoff and Whiteman with no subsequent up-to-date information available) (Blasch, Wiener & Welsh, p270). Robin Leonard (2005, p28) states that 7,000 Americans use Guide dogs. Leonard also references the 1994-95 National Health Interview Study on Disability which indicates that 1.3 million Americans are legally blind, suggesting an estimate of less than one percent for guide dog usage in the U.S.

Adoption rates are low for several reasons. Training of the student handlers and the dog guides is a non-trivial process. The dogs are initially socialized in domestic settings from the age of about 8 weeks until 12-14 months. Once they have reached physical and emotional maturity, they are relocated to the dog guide setting and trained by an instructor for 12-20 weeks. The student instructor and dog guide will work together for 4 weeks to orient the handler and dog guide.

Many factors are considered when qualifying and matching the dog guides and the handlers. For dogs, attributes such as breed, health, temperament, size and behavior are considered. For the handlers, factors include: age, overall health, other disabilities, and acceptance of and comfort with dogs.

2.5.3.2 Tactile Signs. These are the physical signs found on doorways, information kiosks, and elevators. These are made available to users who read by touch. These can have raised letters and/or Braille encoding. These signs are used for labeling points of interest, such as rest rooms, room numbers or auditoriums. These markings are not typically used for other, more general wayfinding information. Tactile signs are often difficult to locate when accessed by blind users. (Blasch, Wiener & Welsh, 1997, p.330).

2.5.3.3 Audible Signs. These devices present speech descriptions of environmental information. The signs are distributed throughout an environment of interest. Landmarks such as "Elevator", "Information Desk" or "Women's Room" can be presented. The playback of speech is triggered and rendered via personal receiver or through a push button located near the sign. In the latter case, playback is through a resident audio speaker and may be heard by bystanders.

A commercial instantiation of audible sign devices is Talking Signs. Talking Signs was originally developed by blind engineers at the Engineering Research Center of the Smith-Kettlewell Eye Research Institute in San Francisco. (Blasch, Wiener & Welsh, 1997, p.331). Talking Signs are installed in an environment and periodically transmit landmark information via infrared transmission; speech description is rendered by a personal receiver. Talking Signs offer an interesting advantage. Due to the directional nature of infrared transmission a user can scan side-to-side and home in on a signal by strength, easily inferring the general direction of travel required to get to the point of interest. A disadvantage of an audible sign approach is cost: an environment must be instrumented with the devices and the users may need to be outfitted with receivers (depending on the implementation chosen).

2.5.3.4 Talking Lights. This clever solution by Talking Lights (www.talking-lights.com) instruments an environment with replacement fluorescent light ballasts. These ballasts modulate the visible light delivered by the lamp using an algorithm that identifies the sensor while eliminating any visible flicker. Users add a PCMCIA adapter to their personal digital assistant (PDA) that reads the data transmitted by the ballast and provides information via voice. By replacing all the ballasts within a building, Talking Lights can provide positional information and provide navigational assistance via linking to a GIS-style database. Talking Lights has a disadvantage similar to audible signs; an infrastructural investment must be made to establish the sensor network. It also carries an additional burden that the GIS database must be established and it must be cross referenced to the installed sensing network.

2.5.3.5 Accessible Pedestrian Signals. An accessible pedestrian signal (APS) is "*a device that communicates information about pedestrian timing in non-visual format such as audible tones, verbal messages, and / or vibrating surfaces*" (Barlow, Bentzen & Tabor, 2003). Details about usage, research, legislation, international comparisons, types, installation, etc. can be retrieved from the National Cooperative Highway Research Program / National Research Council (Barlow, Bentzen & Tabor, 2003).

2.5.3.6 Tactile Maps. Tactile maps are maps that are projected onto paper. The desired features can be printed, but these are primarily embossed to provide the blind user with an ability to interpret the map. There are multiple production methods. Tactile maps have several drawbacks: there is no device for soft copies with sufficient spatial resolution and size, users have difficulty tactually discriminating symbols, maps become cluttered due to the detail of information needed, and lack of training results in misinterpretation (Holmes & Jannson, 1997).

Free downloadable tactile street maps are available from the TMAP project. TMAP is a web-based software tool for rapid production of highly specific tactile street maps of any location in the USA (http://www.ski.org/tmap). Maps are highly customizable; the user can select details they prefer. Also, in an effort to reduce clutter, features and associated clutter are suppressed as the scale increases. For example, only major streets appear as the scale is zoomed out. The GIS data utilized comes from US Census Bureau. The tactile map can be produced on any graphics-capable Braille embosser by the user.

Holmes and Arditi (1997; 1998) studied the relative merits of wall versus path representations on tactile maps when used for indoor route planning by blind users in an unfamiliar space. Wall representations emphasize corridor boundaries through raised features, while path representations construct a more simplified view by displaying a raised feature for the corridor's center. They tested the two variations of tactile map with blind subjects and tested for their knowledge of the map and route plans for prescribed tests. The authors conclude that the wall map was rated higher, but also took more time. There were no systematic effects. They caution that the results may not be generalizable, since many potential users are not totally blind and different layout complexities may cause different results.

2.5.3.7 Electronic Travel Aids (ETAs). A variety of ETAs exist. These typically allow the user to sense objects in the immediate environment, e.g., Loomis' immediate obstacles. They use sound or light and sense the reflected acoustic or electromagnetic energy. Feedback is either vibratory or audio. ETAs are classified by into four different categories: Type I, Type II, Type III and Type IV (Blasch, Wiener & Welsh, 1997, pp. 240-252).

- Type I provides feedback of an obstacle or surface in one's path.
- Type II provides multiple outputs for clearer path detection. Considering a wheelchair bound user, a Type II could present information about forward obstacles and obstacles off to the side.
- Type III builds on Type II and provides additional environmental information. For example, surface texture of an object can be perceived based on varying characteristics of signal timbre.

- Type IV builds on Type III and incorporates computer processing. In the field, Type IV ETAs are known as "artificially intelligent." An example of a Type IV ETA is offered for illustration purposes. Researchers at the University of Stuttgart have developed a Type IV device that permits blind users to explore their local environment and determine characteristics about nearby objects. With a cane device ("blind man's stick"), they can explore immediate surroundings in a manner that is similar to a sighted person's use of a flashlight. The device has a keypad for input beneath the hand and provides feedback via speech synthesis. The device allows the user to determine an object's distance, size and color.

Although near-distance obstacle sensing and ETAs are not of primary interest for this author's work, concepts like discrimination through timbre and processing of multiple concurrent outputs can be.

2.5.3.8 Navigation Systems. Several navigation systems exist that have been created for both academic and commercial purposes. These systems are summarized in the section titled Existing Systems Opportunities for Improvements.

2.5.3.9 Summary of Technological Approaches. Blind users suffer a deficit in wayfinding when compared to sighted peers. Many things are done to minimize this difference: O+M training, assistance from guide dogs, usage of long canes, usage of ETA devices, introduction of accessible pedestrian signals, etc. When considering the technology developments identified in the Technology Landscape section, opportunities still exist to implement information technology, to further reduce the deficit and to improve the wayfinding tools available to blind travelers.

The next section will describe a variety of interfaces that have been developed and evaluated using sound to display spatial information to blind users. These are offered as technology adaptations, attempting to replace information normally provided via vision with sound. These interfaces are considered as a potential means to deliver environmental information necessary for wayfinding as described in this and the preceding section.

2.6 Technology Adaptations for User Interfaces Using Non-Visual Senses

The previous sections in this literature review have considered how people perform wayfinding and what distinctions exist for people who are visually impaired or blind. This section considers how visually disabled persons performing navigation substitute for deprived senses and examines technology that can facilitate this process.

2.6.1 Sensory Substitution

Individuals who suffer from loss of a sense often compensate, usually only partially, by sensory substitution. Loomis (2003) summarizes:

> The traditional way of dealing with blindness and deafness has been some form of sensory substitution – allowing a remaining sense to take over and the functions lost as a result of the sensory impairment. With visual loss, hearing and touch naturally take over as much as they can, vision and touch do the same for hearing, and in the rare cases where both vision and hearing are absent (e.g., Keller 1908) touch provides the primary contact with the external world. However, because unaided sensory substitution is only partially effective, humans have long improvised with artifices to facilitate the substitution of one sense or another. For blind people, Braille has served in place of visible print, and the long cane has supplemented spatial hearing in sensing obstacles and local features of the environment. For deaf people, lip reading and sign language have substituted for loss of speech reception. Finally, for people who are both deaf and blind, fingerspelling by the sender in the palm of the receiver (Jaff 1994; Reed et. al. 1990) and the Tadoma method of speech recognition (involving placement of the receiver's hand over the speaker's face) have provided a means by which they can receive messages from others. (Reed et. al. 1992).

The focus for sensory substitution henceforth will consider blind users, but not deaf or blind+deaf users as also consider by Loomis in the above quote. Loomis identifies artifices employed by blind users that aid the substituted senses.

Within the context of orientation and mobility, it is hoped and intended that further artifices can be developed to aid blind wayfinders in a way that Braille aids the unsighted user with reading. The long cane aids the user with identifying local obstacles; opportunity exists to develop additional artifices that can aid these same users with identification and acquisition of more distant points of interest and destinations.

Both audition and touch are common substitutes for vision, when vision is not present and these senses are responsive for an individual. Due to the proliferation of audio technologies in commodity computing platforms, and the notable absence of haptic capabilities in these same devices, audition will be the output method of focus from here onward.

Audition will be the primary sense considered for vision substitution. Auditory interfaces need to be carefully considered, since "your ears are not simply just eyes for sound" (Stafford & Webb, 2004). As an illustration, consider some of the key differences. Stafford and Webb point out several: vision lets you see *where* something is, hearing tells you *when* it is. There is a difference in human physiology within the time resolution capabilities of the two modes. A cinema screen of twenty four images per second appears as continuous motion, while an audio signal with twenty four clicks per seconds appears as a sequence of clicks. Quadrupling the rate of the audio signal (ninety six clicks per second) will still manifest as discontinuous sound. This physiological difference will present opportunities to sonify numeric data as illustrated below (Walker, Lindsay & Godfrey 2004; Zhao, Plaisant, Schneiderman & Duraiswami, 2004; Zhao, Smith, Norman, Plaisant & Schneiderman, 2004; Blattner, 1989).

Further support for pursuit of audio interfaces for blind wayfinders is suggested by Schneiderman (1992), by extension. Schneiderman enumerates cases where speech is preferred over other user interaction methods. While Schneiderman emphasizes speech, his assertions are extended here by this author to consider audio in a more general sense: the combination of both speech and non-speech sounds. The opportunistic cases he lists are: the user has *busy hands,* the user has *busy eyes*, the user is *mobile*, or the user is operating in a harsh environment. Blind pedestrian wayfinders lack vision (an extreme case of busy eyes) and are mobile by definition. In many cases they will also be 'hands busy', navigating with a long cane, guide dog or human assistant. They may also be traveling with some personal items. So, by considering Schneiderman's advice, blind wayfinders are strong candidates for speech-based user interfaces (and arguably audio, by extension).

2.6.2 Auditory Interfaces

There is a significant amount of research that has been performed in the area of auditory interfaces. Similarly, much focus has been applied to adapting these interfaces for blind and low vision users. This section summarizes core concepts and innovative interfaces that have been developed, mostly within the blind application space. A more general survey of auditory interfaces can be found in the Human Computer Interaction Handbook (Jacko, 2002). The survey provided here focuses on auditory output (auditory displays), excluding auditory input since the focus of the intended work is on auditory display. The innovative approaches reviewed provide a portfolio of potential user interface methodologies, models and widgets for navigating when visually impaired. A survey of constructs and concepts for providing auditory interfaces is provided. Next, a review of interfaces combining auditory displays and touch identifies solutions that have been constructed and evaluated.

2.6.3 Auditory Displays

Auditory displays take on a number of manifestations. Auditory feedback can be provided by spoken word or by non-speech audio. Brewster, referencing papers published as part of the International Community on Auditory Display (Kramer, 1999), describes an auditory display as "using sound to communicate information about the state of a computing device to a user." (McGookin, 2004) Brewster also catalogs components of auditory interfaces, namely: sonification, speech, auditory icons and earcons. Hearcons are an additional construct that has been added to the auditory display landscape. The following section more fully defines the classes of auditory interfaces.

Auditory interfaces exhibit several weaknesses. The quantity of information presented can be much lower than that of comparable visual interfaces. Sound is transient in nature (Pitt & Edwards 1996; Gaver 1989); missed communications may not be easily recovered. Gaver (1989) states:

> "Sound should be used in the interface because hearing is a largely untapped modality for people and because sound production is a seldom exploited resource of computers. However, sound is more than just an available resource. Sound plays an integral role in our everyday encounters with the world, one that is complementary with vision. It is in understanding this role that the most compelling reasons for using sound become clear."

2.6.4 Speech

Speech provides an effective medium to communicate general information. When appropriately constructed, speech can convey information to the user in a form that is easily understood, as identified by McGookin and Brewster (2004). The speech content can be constructed by concatenating audio messages recorded by a human speaker, or generated by a synthesizer such as Cepstral, Festival, Nuance or FreeTTS. Speech displays have achieved wide adoption and apparent success. Examples include subway notification systems, telephone self-service solutions and interactive games.

Speech has several trade-offs that effect its use as an auditory display. The quality of synthetic speech rendering can be difficult to understand. Careful selection of pauses, prosodic controls and information ordering are critical to success (Pitt & Edwards, 1996). Conveyance of numerical information can be viewed as inefficient when compared with sonification-based interfaces or auditory icon interfaces for numerically dense information. Language differences between system designers and intended users can introduce confusion or misinterpretation. Finally, speech processing will impose a cognitive load on the user.

2.6.5 Sonification

Several definitions exist for the concept of sonification in auditory displays. Several are listed and justification is provided to support the definition selected for the work at hand. One definition states "a mapping of numerically represented relations in some domain under study to relations in an acoustic domain for the purpose of interpreting understanding or communicating relations in the domain under study." (Scaletti, 1994). A wider definition supplied by the ICAD Sonification Report (Kramer, 1997) states: "Sonification is defined as *the use of non-speech audio to convey information*. More specifically, sonification is *the* *transformation of data relations into perceived relations in an acoustical signal for the purposes of facilitating communication or interpretation.*" The preceding narrower definition will be adopted for use in this work since the concepts captured by the wider definition are captured more specifically in other definitions of non-speech displays such as earcons and auditory icons (discussed later). Sonification techniques could prove useful for the conveyance of numerical information in wayfinding, for attributes like distance, street address numbers, numerical street names or directional bearing.

2.6.6 Earcons

The seminal work on earcon design and usage was introduced by Blattner, Sunikawa and Greenberg (1989). The authors introduce earcons, an aural counterpart for graphical icons. The authors define earcons as *non-verbal audio messages used in the computer interface to provide information to the user about some computer object, operation or interaction.* The authors further compare earcons to icons: earcons are informational only (icons are selectable and informational) and earcons are transient and demand temporal attention.

Earcons are further described as either representational or abstract. Representational earcons represent essential features of the object that they portray. Abstract earcons are based on a set of fundamental elements, which can be combined to create a large and highly customizable set of earcons. With icons graphic elements are combined, with earcons motives are assembled by varying tones with different rhythms, pitches, timbres, registers and dynamics. Further constructions are possible by combining multiple motives (compound earcons), enabling families of meaning (inherited icons) and conveying temporal changes (transformational earcons).

Adoption of abstract earcons is not without design challenges. In the seminal paper, the authors suggest: "art is to icons as music it earcons." (Blattner, Sunikawa & Greenberg, 1989) The guidance provided by the authors suggested limiting the number of pitches within a motive to no more than four. Subsequent work suggests that this advice can be overridden, but proper attention need be paid to assembling proper musical structure. (Hankinson & Edwards, 1999) Alty and Rigas (1998) express a conclusion that more understanding is required about an average user's perception of musically constructed auditory displays to properly exploit it for efficient interfaces.

McGookin and Brewster (2004) investigated the identification of concurrently occurring earcons. They found that concurrent representation can increase the difficulty of recognizing the encoded contents. They provide the following four guidelines for concurrent usage. (1) The amount of information in an earcon should be carefully considered when concurrent use is anticipated. (2) If register is used to encode a data attribute, these should be implemented with harmonic intervals. (3) When timbre is utilized in earcons, any earcon concurrently presented should use its own timbre. (4) Concurrent presentation should be provided at not less than a 300 millisecond gap, when measured from onset-to-onset.

Earcons offer a rich presentation option for auditory displays and can play a useful role in the construction of a wayfinding solution to communicate environmental context to a user.

2.6.7 Auditory Icons

Several explorations of representational earcons were conducted by Gaver (1986; 1989). Gaver refers to these as “auditory icons” By his definition: A*uditory icons are "everyday sounds that convey information about events in the computer or in remote environments by analogy with everyday sound- producing events."* (Gaver, 1994) These auditory icons represent an underlying system operation, such as providing a scraping sound while dragging a file or a filling sound representing progress while copying a file to a new location. Gaver classifies auditory icons as symbolic, iconic and metaphorical. Symbolic representations resemble Blattner's abstract earcons, where an auditory sound is adopted to represent a message. Metaphorical auditory icons, while still abstract, represent the underlying message with a similar function in the auditory domain. Iconic representations are analogous to Blattner's representational earcons, providing a caricature or simulation in audio of the underlying message. To further clarify Gaver’s auditory icons, consider a file deletion activity: the symbolic auditory icon provides a beep, the metaphorical icon provides a multi-tone motive with a descending pitch and the iconic auditory icon provides a crashing noise as the file is dropped over a wastebasket.

Application of auditory icons, of possibly all types, widens the palette of auditory display options and should prove useful in the construction of a meaningful wayfinding solution for blind users.

2.6.8 Hearcons

Hearcons are three dimensional auditory objects. (Donker, Klante & Gorny, 2002). Based on abstract earcons, these can be placed in 3 dimensional spaces if front of the user. Spatial audio information is provided to the user via headphones or multiple loudspeakers. As the user navigates the space through tablet interface, a "torch" metaphor is applied to expose only those hearcons within an immediate proximity.

2.6.9 Audition and Touch in Spatial Interpretation

A number of interfaces have been developed that permit exploration of spatial data. These interfaces provide feedback via an audio display and often combine tactile input. While the position of this work is to exploit the capabilities of auditory displays for navigation, to the exclusion of haptic interfaces, the following examples in prior work are still provided. These are provided since the interfaces described and evaluated use tactile *input* and audio display output. While navigation applications may not include tactile input, the navigator's location and movement in space can be analogous to the tactile input in the described interfaces.

Two dimension line graphs are examined by Mansur, Blattner and Joy (1985). Variation of the y value of an x-y curve is provided by varying generated pitch, the x axis is varied with time. Users are asked questions about the data (and curve) included in the plot. Comparison to a control using tactile graphs was also performed. Performance for the tactile graphs was slightly better: 88.3% accuracy v. 83.4% for the audio interface (p=0.05). The authors note that the speed to perform determinations with sound appeared to be faster.

An early paper by Mynatt and Weber provides a foreshadowing of future interfaces. These researchers considered both the GUIB project and the Mercator project. These projects provided non-visual access to Graphical User Interfaces

(GUIs). GUIB provided a vertical Braille display, a horizontal braille display, two loudspeakers and a touch tablet. The user can explore the screen space through the tablet touching lightly and receiving speech output. A firmer press navigates the cursor to the identified location. A key below the touchpad allows the user to assert a mouse-press event. (Petrie, Morley & Weber, 1995). Mercator, by comparison, augments existing X Windows desktop system with speech and non-speech audio to convey GUI information to the blind user. The authors predict that the two systems will become enhanced to include the modes and features of each other. As suggested by these authors, and as will be seen in the next section, auditory displays for blind users and wayfinding solutions for blind wayfinders usually combine a mix of speech, non-speech audio, tactile input and braille displays (similar to the aggregate capabilities of GUIB and Mercator).

Friedlander and others created Bullseye menus on touchpads (Friedlander, Schlueter & Mantei, 1998). The Bullseye menu consists of a set of concentric circles divided into quadrants. A menu item is located in each quadrant. Non-speech audio feedback is provided to indicate the quadrant and distance from center (implying direction of stroke). Research showed that visually impaired users could select a large number of menu items, and that the time to perform selection closely approximated performance of systems providing visual feedback. This finding suggests that proper non-visual interfaces can provide meaningful interfaces with acceptable performance characteristics.

Sonification of pen position on a tablet was explored by McQueen (1995). McQueen showed that awareness of location within a 2D Cartesian space using sound is possible. He examined the use of pitch, loudness and timbre as ways of varying sound to orient the user. Varying pitch along one axis and timbre along the other axis provided the best results. Adaptation of this approach and findings for wayfinding purposes may prove useful to this research.

Kennel (1996) showed that a blind user could explore and understand a simple diagram. Exploration was performed via tactile input on an input panel, output was generated as a combination of non-speech audio and text read to the user. Utilization of touch input with generated audio output will be useful in the design a wayfinding solution.

Walker, Lindsay and Godfrey (2004) examine the previously unexplored facet of sonification: point estimation. Using an abacus metaphor, they assign different pitches to the digits zero through nine. By playing digits in succession, an integer value can be rendered for the user. Four notes represent the possible values 0 – 9999. The researchers found that subjects could successfully perform point estimation tasks, with limited introduction and training. The authors also suggest introduction of a "pan" function, separating the represented numbers places in a 2D audio space. Unfortunately, they did not experiment with this implementation. The point estimation capability provides meaningful constructs for a wayfinding solution, potentially for distance estimation, street number addresses or other numerical values requiring display.

Smith and several others found, when creating a tool that allow blind programmers to explore hierarchical file structures, that representing the number of files contained within a subdirectory through non-speech audio got mixed reviews (Smith, Fancioni, Anwar, Cook, Hossain & Rahman, 2004). The researchers followed a Geiger counter metaphor. Many users were distracted by this display, some didn't use it all. Based on these mixed findings, incorporation of point estimation and sonification techniques will need to be considered carefully to avoid the potential of creating distracting UI mechanisms.

Adapting the visual information seeking design guidelines popularly researched, a group of researchers has explored a similar mechanism for use in the design of sonified interfaces (Zhao, Plaisant, Schneiderman & Duraiswami, 2004; Zhao, Smith, Norman, Plaisant & Schneiderman, 2004). They propose the Auditory Information Seeking Principle (AISP). AISP includes four major phases: Gist, Navigate, Filter and Details-on-demand. *Gist* provides the user with a quick grasp of overall data trends and patterns via a short auditory message. *Navigate* allow the user to fly through the data presented. *Filter* provides a capability to seek items that satisfy specific criteria. Finally, *Details-on-demand* provide the capability to obtain details of items of interest. The researchers show that users can perceive data patterns and that AISP fits their users' pattern recognition strategies. For blind wayfinders, AISP could provide a meaningful design methodology to support users' pattern recognition strategies during map reading, planning activities and landmark filtering while under way.

Companion work by the AudioBrowser research team at New Jersey Institute of Technology (Chen, Tremaine, Chung, Lutz & Lacsina, 2006) provides several successful practices in the construction of auditory interfaces. Specifically: (1) Coupling auditory output and gestured input in a two-dimensional physical space. This eliminates the sequential and temporal nature of auditory input while leveraging developed spatial and tactile abilities often found in vision impaired users. (2) The combined use of speech and non-speech audio. Both speech and non-speech can be combined to efficiently provide application status, user interface status, requested information and error messages. (3) Ability to control the auditory output. The user can tailor the interface to optimize operational attributes such as reading speed, resolution (corpus, paragraph, word, character) or volume for their specific needs. Finally, (5) ecological design considerations provide practices that aid in a quality experience. UI layout considers the minimum size of user's fingertips and reasonable target sizes on the touchpad device. Frequently accessed items are placed for ready access. A natural learning convention is implemented: touchpad areas adhere to "touch and tell" while the physical buttons perform "press and execute." Adoption of these practices in a wayfinding interface will provide the same benefits as those experienced with AudioBrowser: performant audio feedback, useful audio feedback, a comfortable user experience and an intuitive environment. Further support for easily learnable interfaces is also provided by Blattner (1989, p 34 and p 40).

The TouchMelody system developed by Ramloll and Brewster (1998) combines tactile input from two hands and provides audio output. The system allows a user to read a tactile diagram where a bar chart is presented on paper, to a blind user, with raised (embossed) lines. As the user indexes both hands across the display varying pitch and timbre is user to convey relative distances. The authors submit several findings. (1) Modifying timbre (switching from xylophone to piano) is effective at conveying relative position (above or below a point) and varying pitch is effective for judging distance. (2) The interface provided the user with an understanding of the underlying data. And (3), there was an unanticipated use of the system: users were able to manipulate a datum (and implicitly scale) to interrogate the diagram at different resolutions. These findings can be applied to a wayfinding solution to help orient users where traditional front/back orientation is problematic via sound and to suggest inclusion of scale manipulation techniques to allow users to interrogate 2D spatial representations at levels dictated by them.

A comparison of three wearable orientation interfaces was performed by Ross and Blasch (undated US Government Work document, 2000). Subjects utilized the system while navigating across an intersection while receiving feedback. Three feedback mechanisms were compared: a virtual sound beacon (also referred to as a Sonic Carrot), a speech interface and a shoulder tapping system. The research found that the shoulder tapping interface was most effective. The authors suggested that a composite tapping plus speech interface may be most effective for a wider population of users, and that the sonic carrot might be effective for people without hearing impairments after more research can be done.

Evaluation of a touch interface with speech feedback for map information was performed by Holmes and Jansson (1996; 1997). The interface was evaluated and compared with a similar interface, where an embossed tactical map was attached to the tablet surface. In the control condition, a grid structure was attached but no location specific information was available. The researchers found that subjects were able to construct a richer mental representation of their intended route after using the touch tablet with detailed tactile map overlay attached. In creating interfaces without this tactile augmentation, it is recognized that potential disorientation by the navigator will be possible.

2.6.10 Audio Interfaces and Augmenting Reality

Although this research does not specifically address the notion of *augmented reality*, it is recognized that enhanced wayfinding tools for blind wayfinders will probably qualify as "augmented reality" environments. Several definitions are included here for reference and comparison:

"AR focuses on presenting information in three dimensions with respect to the user's current position. Users can thus, see, explore, and manipulate virtual information as part of their real world environment." (Sandor, 2005).

"Augmented Reality is an approach to information systems design augmenting physical objects instead of replacing or representing them by purely computer based systems" (Bertelsen, 2000).

Azuma (1997) states three requirements (for an AR system): real-time performance, user registration in three dimensions, and a combined presentation of both virtual and real information.

This section summarized the many candidate auditory interface constructs that are potentially useful for a blind wayfinding solution. The next section will consider existing navigation systems that have been developed for user by blind wayfinders.

2.7 Existing Systems and Opportunities for Improvements

The following section summarizes the systems that have been built for both research and commercial purposes. A brief summary of operation is provided. Strengths and weaknesses are identified. A table follows that summarizes the attributes of the different systems.

The following model identifies and summarizes the key functional components of any navigation system for blind users. The major subsystems are:

user position/orientation subsystem, the geographic information system (GIS) subsystem, and the user interface (UI) subsystem.

2.7.1 Research Systems

2.7.1.1 Talking Braille. This research (Ross & Lighten, 2005) evaluates a system for indoor wayfinding. Points of Interest (POIs), or incremental navigation points (waypoints) are marked with a wireless network of “crumbs.” These “cybercrumbs” are instrumented with infrared broadcast capability as well as speech synthesis ability. Travelers are equipped with a Charmbadge, a transmitter/receiver that interact with the wireless system. Users also carried a portable cell phone device and wore a bone-conduction headset. The proposed system posits an alternative to existing wayfinding / signage solutions. It is argued that Talking Braille provides an inexpensive and ubiquitous infrastructure that can be easily adapted to existing indoor environments.

The envisioned usage is as follows. A user enters a Talking Braille enabled building. Using their Charmbadge device, they locate the first cybercrumb device. Next, they use their cell phone to interact with the building's GIS system to obtain a directory listing, location descriptions and directions. The directions are then followed by navigating waypoint to waypoint using the Charmbadge/cybercrums for incremental navigation tasks. As the user progresses through their route, they are offered instructions via speech presented within an egocentric coordinate system such as: “turn left at the next opening,” “go straight past the next opening” or “keep going straight.” The system is programmed to speak the text of each crumb as the user passes by it. The proposed system also offers alternatives for a less equipped visitor, by assigning a loaned Charmbadge device and neglecting the cell phone device. This alternative is, obviously, less capable and less desirable.

In this research the authors report that the system performance improves navigation by reducing effort (measured quantitatively as excess distance) almost to the point to be comparable with those recorded for fully-sighted individuals. The research did not consider a fully operation system as initially described, but a reasonable subset neglecting the cell phone capability. The authors also report general satisfaction of users when assessed qualitatively, excepting some prototype stability issues and reports that an excessive amount of information being provided.

This system, while interesting and promising, raises several concerns for efficacy. Several hardware components and software systems need to be present for successful operation as envisioned. First, users need to possess a Charmbadge device and appropriate cell phone. Audio rendering capability is required. Next, the building needs to be equipped with cybercrumbs, a Zigbee wireless networking system and server infrastructure to support routing and tracking operations. From a software perspective, the appropriate applications need to be resident and functioning on the cell phone, the Charmbadge, and the GIS server. While installation and orchestration of all the stated components is certainly possible, much progress would need to be made for this solution to be adopted in a universal way.

2.7.1.2 Personal Guidance System. The system, as presented by Loomis Golledge and Klatzky (1998), follows Loomis et.al's (1994) earlier model for a navigation system for blind users. Users are equipped with a backpack device, which contains: a 486 sub-notebook computer, a differential GPS system and audio processing equipment (see Figure 2.1 and Figure 2.2). The GIS comprises a detailed database of the test site. The user interface is provided by rendering spatialized audio sound or speech to the user that displays waypoint (turning point) information. The Personal Guidance System project and research deal mostly with the design of the GIS system and the user interface (UCSB website, 2006).

The research presented only considers traveler guidance along a predefined route. Guidance performance of four different display modes is collected, analyzed and compared. The authors find that spatialized audio from a virtual acoustic display (Display mode 1) is best when compared to displays utilizing variations of verbal commands delivered via synthetic speech (modes 2-4). In mode 1, waypoint identifiers are spoken by name (i.e., “One”, pause, “one”, pause, “one”, etc ...). The spoken identifier appears in a binaural headset display as coming from the location of the waypoint in the horizontal plane, so users can orient and walk toward the point of interest. The intensity increases as the user approaches the destination. User preferences and guidance performance were both better with the first mode.

Figure 2.1 Personal guidance system - early days.

(Source: UCSB, 2006)

Figure 2.2 Personal guidance system in 1993.
(Source: UCSB, 2006)

Subsequent research has extended the perceptual display capability of PGS to incorporate the Haptic Pointer Interface (UCSB, 2006). The HPI incorporates a handheld component that contains both an electronic compass and a loudspeaker or vibrator. The device provides feedback as a user orients it towards or away from the destination point. As in the acoustic interface, intensity increases as the wayfinder approached the destination. Similar to the earlier virtual acoustic display, the PGS researchers provide a perceptual display in addition to (or in place of) rendered speech. They assert that users want and prefer this rich interface to the environment.

PGS provides significant insight and guidance into development of visually impaired navigation systems: (1) blind users, over almost two decades of research and development, express a preference for perceptual displays that convey environmental information while wayfinding and (2) positional information is not enough; user orientation information is required for successful navigation.

2.10.1.3 Dog+ PDA Based Personal Guidance System. Dog+ is a proposed navigational assistance system designed for usage by blind users on PDA devices. It extends and aggregates several underlying systems for specific functionality. The underlying systems are: BATS – an audio interface for maps (note: reference for BATS is unpublished work), (2) LineDrive (Agrawala & Stolte, 2001) – a map generalization algorithm for driving directions and illustration, and (3) Cricket (Priyantha, Chakraborty & Balakrishnan, 2000,) a mobile location sensing solution. The paper focuses on the extension of map generalization and adaptations for audio as well as the intended graphical usage.

This system, having been proposed but not implemented, appears to be a very ambitious undertaking and in some parts difficult to carefully consider. The paper describing the audio interface for BATS is unpublished, making it difficult to assess its efficacy. By the author's own description, BATS is graphically oriented and would need redesign to apply it to Dog+. Furthermore, the proposal references spatial audio icons, but it runs on a PDA device and no discussion or provision appears for binaural sound production. The author has proposed using the volume of the spatial audio icons as an indicator of distance. Research has found that modification to pitch/rhythm or timbre will provide more meaningful feedback (discussed in the *Auditory Displays* section).

Adaptation of the Cricket location solution integrates work of Priyantha et.al. and appears to be straight forward.

Some concerns arise in the area of applying the LineDrive (previously MapBlast) technology. The author argues that adaptation from a road/driving domain to blind use/walking domain would be straightforward. Construction of a prototype and validation with test subjects would be desirable to confirm this assertion.

The paper does propose an interesting approach to zooming. The map space presented on the PDA's input screen is segmented into a 3x3 grid, button gestures are used to zoom in to selected grid cells and conversely to zoom back out. Auditory tones are structured to reflect the level of zooming, so that the users can quickly ascertain their level within the zooming hierarchy (Vogel 2003, p 13).

2.7.1.3 MoBIC Travel Aid. The MoBIC travel aid was a research initiative carried out in the mid 1990's. It intended to aid blind and elderly travelers with navigational tasks. It focused on macro-navigation, similar to Loomis' acquisition of destinations. It deemphasizes micro-navigation, which concerns local obstacle avoidance (again, similar to Loomis' classification of obstacle/hazard avoidance). The system had two primary components that considered two phases of navigation: the MoBIC pre-journey system (MOPS) and the MoBIC outdoor system (MoODS). MoPS also considered integration of non spatial data such as mass-transit timetables, but these were only envisaged (Strothotte, 1996).

The article retrieved that describes MoBIC was a preliminary overview and suggested follow on articles would summarize field results. This search did not find the follow on results.

The following retrospective summary was retrieved from the MoBIC website (MOBIC, 2006):

> The MoBIC project ran from the beginning of 1994 to the end of 1996. The aim of the project was to increase the independent mobility of visually disabled and elderly people by developing an orientation and navigation aid based on technology emerging for non-disabled travelers. The aid developed builds on the technologies of geographical information systems (GIS) and

> Global Positioning System (GPS). The MoBIC Travel Aid (MoTA) consists of two interrelated components: the MoBIC Pre-journey System (MoPS) to assist users in planning journeys and the MoBIC Outdoor System (MoODS) to execute these plans by providing users with orientation and navigation assistance during journeys. The MoTA is seen as being complementary to primary mobility aids such as the long cane or guide dog. One outcome of the project was a detailed specification of user requirements which is largely device independent. (MoBIC, 2006)

2.7.1.4 Location Guidance System by Ogata and Others. Copied from McCabe (undated) in the absence of a Japanese to English translation of the original work:

> Another promising indoor navigation system is the one proposed by Ogata et. al. (1997). This system uses "invisible" barcodes that look like white pieces of paper but contain information that can be read by an infrared scanner. In an experiment, Ogata et. al. placed these invisible barcodes along the length of a hallway and used an infrared scanner to scan the barcodes as they walked down the hallway (1997). The experiment was successful; the researchers were able to read the barcodes with 100 percent accuracy at normal walking speeds. While the barcodes in this particular experiment did not contain any useful information, the researchers believe that they could be used to indicate doorways, hallway intersections, etc. in a building (Ogata et. al., 1997).

While this system is potentially useful for low vision navigation, it has the same problem as the Talking Signs system cited previously: the cost of installing the system into a building. In this case, the cost is associated with creating and installing hundreds or thousands of invisible barcodes throughout a building. While it may not cost as much as the Talking Signs system, an invisible barcode system would still be a large financial burden to the owner of the building.

2.7.1.5 System for Wearable Navigation by Walker and Lindsay. Walker and Lindsay build an evaluation system based on a larger system, the System for Wearable Navigation (SWAN) built at Georgia Institute of Technology. In published research (Walker & Lindsay, 2006) using their SWAN virtual environment, they compare the effects differing display modes, capture radius and practice. Capture radius is defined as the tolerance with which a traveler must be near an actual waypoint to satisfy an 'arrival' condition. The larger SWAN system provides infrastructure and support for full-scale outdoor navigation, while a scaled, virtual environment provides simulation within a room. In this scaled environment, the subject wears a stereo headset and head tracking device. The user's direction is reported by head related transfer function (HRTF) data provided by the head tracker. The user's location in the virtual environment is determined as follows: the stationary user navigates by turning in place and gesturing with a joystick trigger to indicate forward (walking) motion. The 3D audio is provided through the OpenAL rendering library.

2.7.2 Commercial Systems

2.7.2.1 Strider / Arkenstone. Arkenstone's Strider, dating back to 1994, was an early commercial offering in the blind navigation space. Strider was based on a backpack-based computer system with a keypad for user interaction. The Strider provided its information to the user via speech synthesis. According to a much later Sendero product video (Sendero, 2006), the Strider product received a lot of positive coverage from the news outlets at the time. Also, according to that same video, the Strider became obsolete and outlived its useful life; it became too "cumbersome" and "bulky" for everyday use.

Due to funding limitations, work on Strider was suspended in 1998. (Fruchterman, 1998). The entire Arkenstone product line was sold in 2000 to Sendero Group (AccessWorld, May 2000.)

2.7.2.2 Trekker by VisuAide (now Humanware). Trekker is a PDA-based GPS system to help blind and visually impaired persons navigate in urban and rural areas. Trekker provides assistance with details about local area attractions and directions to specific destinations. The system works anywhere in the world. Maps are available for most Western countries. The Trekker is also available with the Maestro option, which provides a full range of additional functionality. Specifically, the device is expanded to include: agenda, text notes, voice notes, address book, DAISY reader, media player, email, web browser calculator, clock and alarm functions.

2.7.2.3 Humanware Notetaker w/ Sendero's BrailleNote GPS. Sendero's BrailleNote GPS is an add-on module for the Humanware BrailleNote product. It is also available directly from Humanware. Version 3.3 will run on the mPower (laptop form-factor) or PK (PDA form-factor) platform.

Figure 2.3 Humanware system.
(Source: http://www.humanware.ca/web/en/p_DA_BrailleGPS.asp)

The accompanying database provides 12 million points of interest (POIs). Users can navigate to POIs, set their own POIs, or explore an environment using the "Look Around" feature. "Look Around" provides speech descriptions of local features such as the names of streets, intersections, stores, churches, etc. Directions are provided with a couple of buttons. Sendero declares that the BrailleNote GPS is "the Cadillac of accessible GPS systems." Sendero reports that studies at Western Michigan have shown that users will find their destinations more easily and know more about their surroundings than without using this solution.

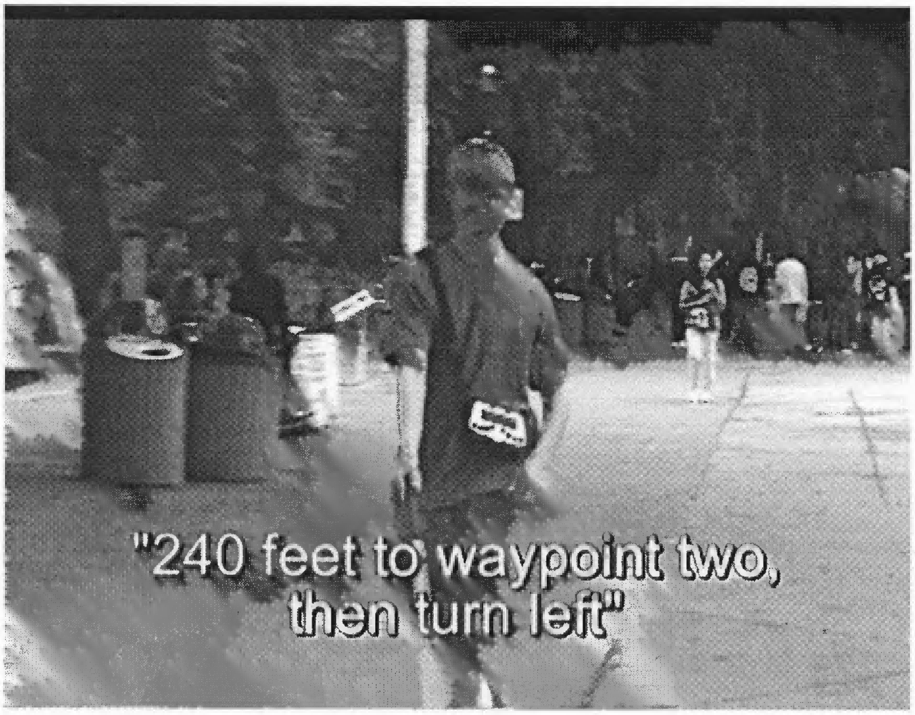


Figure 2.4 Illustration of user navigation.
(Source: Sender Group video, 2006)

"31 feet ahead"

Figure 2.5 Arrival at destination.
(Source : Sender Group video, 2006)

2.7.3 Comparison of System Features

The features and capabilities of the reviewed systems are summarized in Table 2.3. Several noteworthy observations include: (1) systems are either outdoor use or indoor user, none are all inclusive (2) the resolution of all the systems deployed is not less than 1m (3) there are only 2 systems that are commercially available at the time of this search, and (4) the existing systems are not inexpensive.

Table 2.3 Blind User Navigation Systems

System	**Orientation?**	**Commercial**	**Location technology**	**Platform**	**Input**	**Output**	**Indoor/ Outdoor**	**Resolution**
Talking Braille	None (on calibration equipment only)	No	IR (ID and text) ZigBee network for server communications	CharmBadge or Cell Phone	Kiosk or cell phone keypad	Text message, prerecorded audio, Sign ID	I	30 ft
Personal Guidance System	Fluxgate compass	No	DGPS	486 sub-notebook computer	Keypad	Speech or spatialized sound	O	1 m.
Dog +	None	No	Cricket	PDA	Speech text or pointer based	Audio (compound earcons + speech)	I	4 ft.
Mobic Travel Aid	Yes	No	GPS	Handheld computer	Keypad	Speech via ear piece	O	5 m.
Location Guidance System Ogata (et.al.)	Unknown	No	Infrared / Barcodes	Cell Phone	Unknown	Unknown	I	Unk.
SWAN Virtual Environment	HRTF	No	Simulated	Personal Computer	HRTF + joystick trigger	Non-speech audio via OpenAL	I	n/a
Strider	No	Yes	GPS	Backpack computer	Keypad	Speech	O	5m.
Trekker ($1595 US including PDA)	No	Yes	GPS	PDA	PDA button overlay	Speech	O	5 m.
Humanware ($6600 US including BrailleNote mPower QT18	Reports "direction you are traveling"	Yes	GPS	Mpower (laptop) or PK (PDA)	Keyboard	Braille display + speech	O	5m.

The previous sections have inventoried and analyzed technologies, wayfinding principles and wayfinding strategies for both sighted and unsighted users. This section provided a survey of existing research and commercial systems that provide navigation capability to blind travelers. The next section will discuss methods and measures established for evaluation of wayfinding systems.

2.8 Evaluation Methods

Objective measures commonly employed in evaluations are measured for users following paths or instructions to predetermined destinations. These are distance traveled and elapsed time. (Ross & Lightman, 2005; Loomis, Golledge & Klatzky 1998).

Users' performance with the system in question is compared to control groups. The control is established by comparison to the transit time and distance for a sighted user, or by comparison to performance obtained by assistance from an informed bystander (Holmes & Arditi, 2000; Reedijk & Whitehouse, 1999; Ross & Lightman, 2005).

Additional measurements may also be employed. In addition to those listed, Ross & Blasch (2000) recorded off target error, out of crosswalk error, hesitations and any apparent subject confusion.

Subjective measures are employed to assess participant ratings of the system under evaluation. (Ross & Lightman, 2005; Loomis, Golledge & Klatzky 1998; Strothotte, 1996).

The following section provides a summary of the literature reviewed and provide suggestions for follow on research.

2.9 Summary of the Literature Review

There are a large number of people who will be visually impaired and blind in the future as reported. They will require assistance if they are not to remain shut-ins and isolated individuals. Blind travelers are challenged in understanding and navigating within their environment. Lack of vision deprives the blind user of valuable information that aids their sighted counterparts. Significant development, affordability and availability of technology provide an opportunity to narrow the gap between blind wayfinders and sighted wayfinders. Providing environmental information to blind wayfinders will improve their ability to navigate their physical surroundings. Affected people and society at large will benefit by the continued independence of this growing, aging community.

There is a great deal of research and development that has been performed in the areas related to navigation by blind people. As discussed by Loomis, navigation tasks decompose into (1) nearby obstacle and hazard identification and (2) destination acquisition. Focusing on the first component, obstacle and hazard identification has been underway for a long time and is quite mature and well understood. The second component, understanding the environment and navigating to remote destinations, is a more undeveloped area and offers great opportunity for modern technology adaptation.

Application of technology for use in navigation systems by blind travelers has been limited, to date, for the following reasons:

- Focus is often on the nearby hazard avoidance rather than route planning, spatial understanding and wayfinding
- Fine grained instrumentation for location and direction has not existed in readily available formats

- Investments for the dedicated infrastructure required to provide location and directional information for blind wayfinders has been very expensive

The proposed work of this research is to generate technology to provide wayfinding and navigational assistance to blind users by (1) taking full advantage of infrastructural and technological improvements to reveal meaningful information about the environment the user travels, (2) building on the research of wayfinding and spatial understanding for both sighted and unsighted users and (3) building on the research showing that sound can be used to provide feedback for navigation.

CHAPTER 3

DESCRIPTION OF THE taux SYSTEM

3.1 Overview

Multiple, personal navigation systems have been developed, in both the research and commercial domains, for use by visually impaired and blind users. Many of these systems use sound as a feedback mechanism for presenting relevant information to the end user. In parallel to this development of the navigation systems, various sound displays have been investigated by the research community for the presentation and understanding of spatial information. Of the sound displays researched, only a small percentage of them have been applied to these navigation systems. It is possible that the choice of sound feedback is key to effective navigation with these systems, but these sound feedback systems have not been studied. As is typical in interface design, disciplined study of user preferences and the performance of potential implementations are required to understand their relative merits. Construction of a navigation system is non-trivial because these have several complex subsystems that are tightly integrated. Creating a sound feedback evaluation system that is tied to navigation tasks could be a way around this problem. If such a system supported virtual navigation and the ability for the experimenter to generate many variations in sound feedback, one could easily test many sound displays with human subjects. This chapter describes an evaluation system that has been implemented.

This chapter will present the following. First, an illustrative example is provided to provide a context and set an anchor for the concepts and constraints discussed subsequently. Secondly, a summary of the requirements collected for the desired system is offered. Next, the selection process that was followed for the required subsystems is summarized. A summary of the problems that were encountered in building the system is provided. The following section describes the basic operation of the implemented system from an investigator's view. Next, a detailed discussion presents the technical details of the implemented system. Finally, guidance is provided to the future experimenter interested in modifying the configurable settings of the delivered system, or, for the more ambitious experimenter, guidance on how to extend the existing tool set to include completely new auditory display mechanisms.

A real world navigation example is now provided to illustrate the main subsystems and their functions. This example will be carried throughout the chapter to further clarify and refine the descriptions of the various aspects of the system.

3.2 Illustrative Example

A blind pedestrian traveler, Ben, is navigating through city streets. He is currently located on Jackson Street, and wants to proceed to his pharmacy, which happens to be at 12 West Elm Street. Figure 3.1 shows Ben's situation.

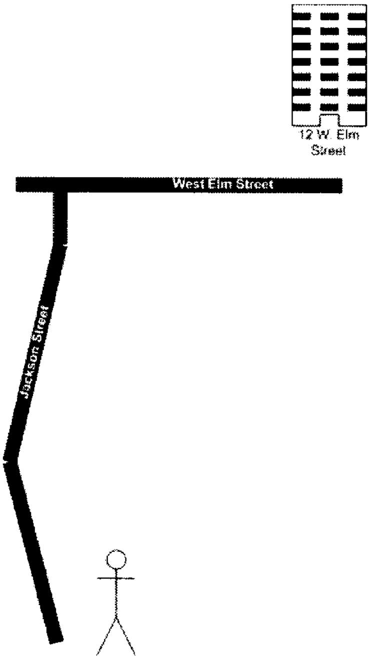


Figure 3.1 Ben's navigation.

With a fictional navigation system, Ben would proceed as follows. Ben uses a headset connected to his cell phone. In addition to providing telephony services, Ben's phone offers audio navigation assistance. Ben instructs his phone simply by speaking to it. He asks the device to guide him to his pharmacy, since he wants to pick up a prescription. The phone responds by telling Ben that he needs to re-orient himself, by changing direction, slightly to his left to follow along Jackson Street. The device senses Ben's location and direction as he turns his body and tells him to stop turning when he's pointed in the proper direction. Ben is instructed to proceed forward. Ben now walks in the direction that he is pointing. As he progresses, the devices offers assistance to turn slightly left or slightly right if Ben veers off course. Once Ben corrects his direction, the device informs Ben that he is again facing the right direction. Jackson Street is relatively straight, but it does have one slight bend. As Ben approaches the bend, the system signals that a change of direction is coming soon. When Ben arrives near the bend, the device instructs Ben to turn to his right until he once again points in the proper direction. Once Ben's direction is properly adjusted, Ben is prompted to walk forward.

As Ben approached the intersection of Jackson and West Elm, the system again notifies him of an impending change. When Ben reaches the intersection, he is guided across the street and then instructed to turn to his right until he is pointing in the right direction to follow West Elm Street. Once he is pointing in the proper direction, he is instructed to move forward. As the destination approaches, Ben receives status updates and then confirmation of arrival.

Although the example provided is practically possible with existing technological capabilities, it currently exists in only crude research prototypes. It is a high level, stylized view of what a future system may provide. A closer look will reveal the required subsystems that must be present in such a test system. It is hoped that this stylized view will be possible in the near future, and it is the intent of this work to support continued development on one of the needed subsystem components.

3.3 A Closer Look at the Illustration

Ben first instructed the system that he wanted to travel to his pharmacy. Several things happened behind the scenes. The user interface accepts Ben's command input, consults with his local address book, and translates this to an instruction to navigate to the pharmacy's address. The device also determines Ben's location and orientation. The device interfaces with an external location sensing infrastructure to make this determination. The device now communicates this location information and the previously constructed instruction to a geographical information system (GIS). The GIS can do several things with this request: it translates Ben's pharmacy name to an address (if this has not been done), it plans the route to the address, and it provides the detailed list of intermediate steps to complete the entire route. It could also provide multiple options for routing and negotiate with Ben to identify his preference based on other factors (avoid construction, avoid busy intersections, pass by the post office; etc.). The previous example assumes no such negotiation was required.

Once this processing is complete, a software agent must continuously correlate Ben's position, orientation and progress with the planned route during navigation. This agent interfaces with the location sensing infrastructure, the user interface and the GIS. For simplicity, this agent will be called the botGuide (within the software described subsequently, this agent is also referred to as the NavigationManager). As events warrant, the botGuide will interact with the user interface to present Ben with timely messages.

In this closer look, the key subsystems of a navigation system were identified and illustrated: the location sensing system, the GIS, the user interface and the botGuide.

3.4 A Simplified Illustration

In the introduction, it was argued that evaluation of many sound displays could yield improvements in navigation systems and improve the overall experience for travelers. In the Illustrative Example, a fictitious scenario was presented that projected a desirable future state. In this, a more simplified example, an evaluation system is described that is possible today and more closely focuses on the stated goal of improving auditory feedback while navigating.

Benji, a college student, is participating in a Ph.D. research project. The experiments are conducted in the University's gym. A temporary location sensing system is constructed in the gym. This is an indoor system and is currently available for use in factories and office buildings; it provides highly accurate resolution for location, user orientation and reporting frequency. The student wears a binaural headset that is connected to a laptop. The laptop is suspended in a backpack and worn on the back. The laptop communicates with the sensing infrastructure using standard wireless networking protocols. All of the software functional components: the GIS, the botGuide and the UI are resident on the backpack laptop system. Benji stands on a predefined location on the gym floor marked by a piece of tape. This is the start point for the route Benji will follow as part of the research project. Next, he follows verbal instructions and listens to sounds provided by the experimental navigation system. Listening, he follows a pre-defined route by proceeding into intermediate locations within the gym space. Benji could be sighted, visually impaired or blind; the system will perform for subjects in all three categories. Performance measures are collected as Benji travels over the predefined route.

In this simplified illustration, much of the complexity presented in the original illustration has been eliminated. The fundamental task of a navigator acquiring the next destination has been preserved and emphasized. An implementation with the primary system components (location sensing, GIS, UI and botGuide) are provided. The system supporting the gym scenario has several distinctions from the fictitious one provided earlier. As previously stated, complexity has been reduced. More specifically: pharmacy name to address mapping has been eliminated, route planning has been substituted with a simpler model, and interference with immediate obstacles and hazards has been significantly reduced. In addition to reduced complexity, variation introduced from real world systems is also minimized. Location accuracy, direction accuracy, and location reporting frequency are all improved by at least an order of magnitude. Speech recognition and natural language understanding concerns have been eliminated. Finally, those capabilities currently not available or mature enough have been mitigated. (For example, free form, speaker independent speech processing capable of noisy environments is not needed.)

The simplified illustration is provided as an aid to further define and describe the system developed. In the system description that follows, more simplifying assumptions have been made that further constrain the environment and closely focus on auditory display of navigational information. These assumptions will be provided and a system with further refinements will be described.

The following section now lists the requirements that were collected for the evaluation system.

3.5 Requirements

The requirements are specified in one of two categories: requirements that the system *shall* implement and requirements that the system *should* implement. The *shall* requirements for the evaluation system are enumerated in Table 3.1.

Table 3.1 System's 'shall' Requirements

System Requirements. The system *shall*:	
I.D.	*Description*
A.1	implement the primary components: location sensing system, a GIS, a UI and a botGuide.
A.2	contain or interface to a location sensing system that reports a user's location and their body orientation.
A.3	perform such that the subject perceives the detected location and audio feedback to be happening in real time.
A.4	support modification of parameters that map to independent variables such as the route definition used and the sound display employed.
B.1	be flexible, allowing adaptation of sound display to try new feedback mechanisms .
B.2	measure navigator performance in the form of time to completion, distance efficiency and veer.
B.3	support the reporting of performance data to external applications .
B.4	provide a sampled, time stamped log of user location and direction while navigating .
C.1	allow the recording of time-stamped tags in the log for exceptional events as identified by the investigator .
C.2	support the ability to perform descriptive and inferential statistics on the collected performance data.
C.3	support training and experimental modes.
C.4	provide a capability to create route data (or to import it from an external application).
D.1	provide feedback to the investigator to determine when to complete training based on learning criteria.
D.2	provide clear unambiguous speech when presenting information.
D.3	be safe for subjects to use.
D.4	provide a 3D virtual reality environment for modeling various spatialized sounds.
E.1	provide location accuracy of 1/2 of a human body width or better.
E.2	not agitate or annoy the user.
E.3	support a repeatable experimental environment.

Additionally the system should fulfill the requirements identified in Table 3.2.

Table 3.2 System's 'should' Requirements

System Requirements. The system *should*:	
I.D.	*Description*
F.1	utilize off-the-shelf and open source components where possible.
F.2	be inexpensive.
F.3	be portable.
F.4	provide update frequency of once per step (or better) during travel while walking.
G.1	be easily extended or adapted to support the gym scenario, NJIT's SmartCampus or city navigation.
G.2	contain or interface to a location reporting system that is capable of reporting both body and head orientation.
G.3	provide the capability to adapt new platforms in the future: game consoles, cell phones or other devices.
G.4	be polymorphic and extensible to easily allow for future adaptation.

3.6 Solutions Survey and Analysis

As previously established, selection of the proper subsystems for location sensing, a GIS, the user interface and the botGuide must be performed.

Needing to start somewhere, it was decided that identification of the location sensing subsystem would be the best place to start. It was anticipated that implementation of this subsystem could be the most difficult, since integration must occur with existing infrastructure or physical assets must be acquired, approved, installed and maintained. Since the other functional subsystems are more software oriented, these could be selected and adapted to work with the location subsystem once it was identified.

3.6.1 Location Sensing Subsystem

Several alternatives were explored. Initially, it was hoped that integration could be accomplished with existing infrastructure, greatly simplifying the burden on this effort. NJIT's SmartCampus infrastructure was considered, but it was eliminated since it did not meet the requirements for location accuracy and reporting frequency. Additionally, it offered no reporting of a user's direction, so some additional augmentation would have to be added (for example, a digital compass worn by the user).

Another existing infrastructural component was considered. If experiments were to be conducted outdoors, existing GPS infrastructure could be utilized using either a hand-held GPS, a laptop with a GPS card or a GPS enabled cell phone. As in the case of SmartCampus, location accuracy and reporting frequency were not adequate. Also, as with SmartCampus, augmentation would need to be added to determine the user's direction.

Having exhausted obvious existing infrastructure solutions, other solutions were surveyed. Using Radio Frequency Identification systems (RFID), similar to the barcode approach previously described by Ogata et. al., an implementation could use an RFID tag distributed at reference points or worn by the subject to determine their approximate location. It was determined that most RFID systems do not provide the location accuracy needed. Many are omni-directional, and do not identify tag observation more accurately than seeing them within a specific distance of the sensor. Additionally, increasing sensor power to improve accuracy proved problematic since this places subjects at risk of unacceptable radio emission levels.

The most promising of the RFID offerings was a solution offered by Ubisense, which employs ultra-wideband frequency tags that communicate with sensors and a central processing system. The system is commonly employed in factory and office settings and is suitable and safe for tracking the location of people. The system offered location accuracy, direction accuracy and reporting frequency that met the evaluation system's requirements. Unfortunately, the system cost was non-trivial and this work is being provided without funding. Recall that requirement F.2 states a goal of the system being inexpensive. Additionally, implementation would require a permanent or quasi-permanent installation that would not meet the desirable system feature of being highly portable (requirement F.3).

The initial findings of the survey of location sensing technology were disappointing. It was suggested that a non-conventional approach was needed, so, exploration was widened and directed elsewhere.

The inspiration for the selected location sensing solution comes from work done by Jefferson Y. Han at New York University (Multi-touch, 2007). Similar work has been demonstrated by Mitsubishi Labs (Mitsubishi, 2007). Han created an application that uses a touch display which allows the user to interact with a map by touching it with two hands. He demonstrates how a user can easily rotate and scale the map with simple natural gestures on a flat display device. Although the device and method demonstrated are not directly applicable to the evaluation system being designed, this example provided the motivation to seek a scaled environment that a subject could manipulate similarly to simulate navigation in the real world.

In evaluating scaled systems, several alternatives were considered and subsequently eliminated. Three are discussed as follows. A Logitech 3D mouse was considered. The physical configuration of the 3D mouse consists of a tethered mouse-like device with a rotating knob that sits on top of it. This device was eliminated, since the physical configuration decouples rotation from translation and necessary mental transformations would add a cognitive burden to the subject if employed in the evaluation system. Using a standard mouse or touchpad was also considered. Related work by the Audiobrowser group at NJIT has shown that applying a mouse or touchpad to problem domains requiring absolute (versus relative) coordinate systems is problematic. Additionally, some augmentation would need to occur since the mouse has no way of sensing and reporting its direction. Another alternative considered was to use a tablet PC device. Again, with the absence of directional information about the user (projected through a finger or stylus), this alternative was removed from consideration. Finally, a multi-axis 'space ball' input device was considered. It, too, was eliminated due to difficulties with relative versus absolute coordinate systems reporting (similar to the mouse / touchpad).

The device selected was a digital drawing tablet, commonly used by graphic artists. Specifically, the device selected is a Wacom Intuos 2 XD-0912-U with a drawing stylus and a 4D mouse. The stylus is not used. The 4D mouse reports x and y coordinates, as well as direction. With data from this device, the evaluation system can easily determine where the 4D mouse is and which way it is pointing. In the system design and during the studies this device will be referred as the "puck," to avoid confusion with mice and any pre-disposed notions about them. This digital drawing tablet device meets the requirements of the evaluation system: it allows the user to navigate in a 2D space, it reports frequently, and it provides directional information when using the puck. Additionally, it is very portable.

The tablet-based, scaled location sensing subsystem allows further constraining of the problem domain. In life scale environments like the city street or the gym, environmental factors limit the ability to conduct experiments: variation in weather can affect user efficiency and sensing quality, ambient noise can inject non-deterministic distractions, and scheduling difficulties can limit control. For example, basketball practice in the gym or rush hour traffic in city streets will introduce conflict and variance. Limiting navigation to a virtual space via an invisible map mitigates many influences of conflict and variation.

One difficulty encountered with the Wacom tablet device is meeting the requirement of platform neutrality. The libraries available for programmatic access are specific to the Microsoft Windows platform. This incompatibility was analyzed and addressed. By interfacing to the Wacom libraries via the Java Native Interface (JNI), a platform neutral implementation can still be developed in Java while allowing for access to the Microsoft Windows specific library. The jwintab library was tested and selected to provide the JNI implementation (http://www.csl.sony.co.jp/person/rekimoto/java/jwintab/).

Once the selection of the location sensing subsystem was completed, the remaining subsystems are evolved in parallel. These are discussed next.

3.6.2 GIS Subsystem

The GIS Subsystem selection is considered next. The GIS contains information about places; it associates this information with the encompassing spatial environment. In the prior *illustrative example*, the GIS was responsible for mapping places to addresses (and, ultimately, to coordinates in the environment), for determining optimal navigation routes and for optionally determining alternate routes. Basically, the GIS is consulted to resolve user intentions to spatial locations and navigation vectors. Within the context of the developed evaluation system, the GIS can be greatly simplified. Since navigation is bounded to the extents of the drawing tablet, and since the desired routes are to be controlled closely for experimental control conditions, the evaluation system's GIS subsystem results in (1) a collection of predefined routes (as a series of x and y coordinate pairs) and (2) the application data structures and methods to manipulate them in the evaluation system. The GIS subsystem selected and employed is "homegrown;" it is built completely within the evaluation system.

The initial routes were manually defined and stored as text files. As practice testing was performed, it was identified that a need existed to either (1) build a graphical route creation and maintenance tool, or, (2) interface to an existing tool. Since mature, robust tools exist to edit and manipulate 2D data it was decided that these capabilities should be leveraged by interfacing to an existing system. Since this author has extensive experience with interfacing to Medusa 2D CAD system (http://www.cadschroer.com) and the vendor was willing to offer a no-cost research license to support this research, Medusa was identified as the existing system to use. Initially, in the absence of the research license, paths were created and managed with a non-commercial, limited version of the software. Since programmatic interfaces are disabled in this free version, path coordinates were manually transcribed into the evaluation system's data files. At present, the license has been secured and future work will programmatically integrate the evaluation system with Medusa. Once that is interfacing is complete, users of the evaluation system can quickly define or edit paths in Medusa and use them in the evaluation system. The planned programmatic interface will use AutoCAD's data transfer file (dxf) format for interfacing, so any CAD software package capable of importing dxf will be able to author and edit paths for experiments. Figures 3.2 and 3.3 show the same sample navigation route in the Medusa system and in the taux system, respectively.

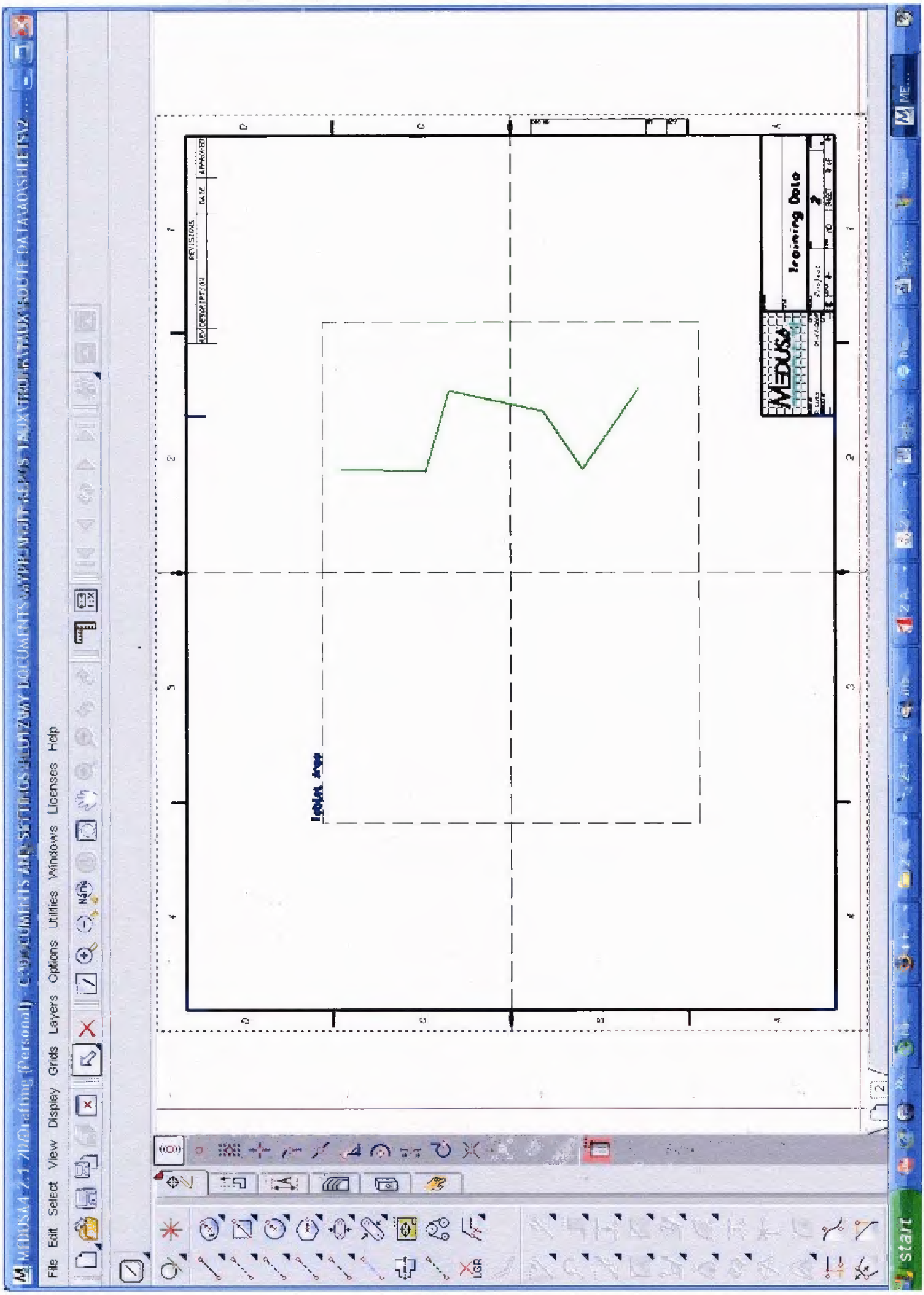
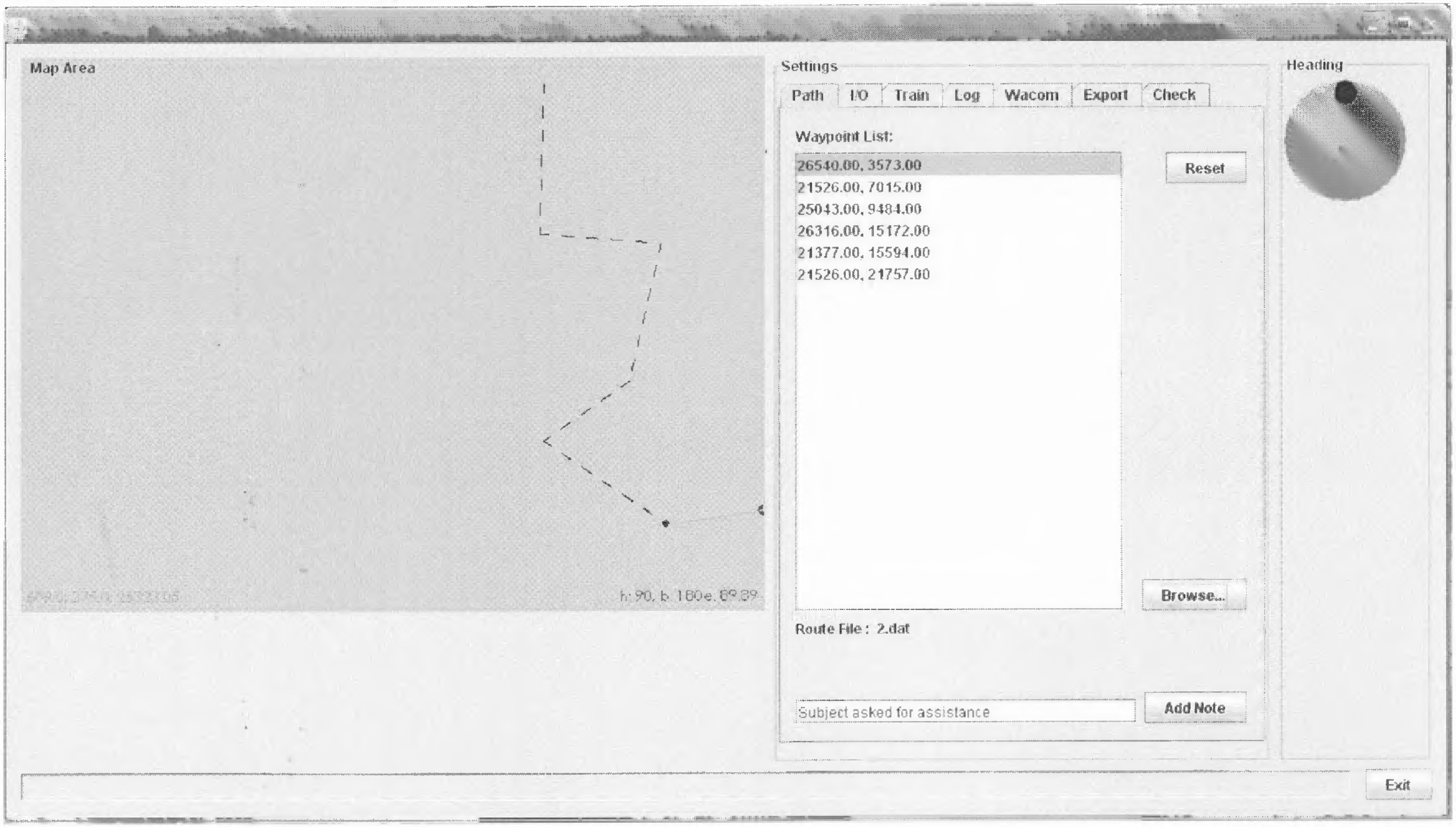

File
Edit
Select
View
Display
Grids
Layers
Options
Utilities
Windows
Licenses
Help
REVISIONS
DATE
APPROVED
MEDUSA
Training Data
start

Figure 3.2 Navigation path in Medusa 2D CAD system (solid line shown in green.)


Map Area
h:90, b:180e:69.39
Settings
Path
I/O
Train
Log
Wacom
Export
Check
Reset
Browse...
Add Note
Heading
Exit

Waypoint List:

26540.00, 3573.00
21526.00, 7015.00
25043.00, 9484.00
26316.00, 15172.00
21377.00, 15594.00
21526.00, 21757.00

Route File : 2.dat

Subject asked for assistance

Figure 3.3 2D Navigation path in evaluation system.

In a real environment like the city street or even in the hypothetical gym environment, physical attributes like streets, curbs and doorways need to be considered by a complete GIS. These environmental features add complexity without adding anything to the quality of the audio display experiments. In fact, the opposite may be true, navigation of immediate obstacles may present challenges to various subjects in unequal ways introducing variation to experiments. As an example, a user with a white cane may experience different latencies when encountering a curb than another subject who doesn't use a cane and has increased light perception. By using a simple GIS system environmental influences are reduced; potentially reducing variation in the experiments.

Next, the user interface components will be discussed.

3.6.3 User Interface Subsystem

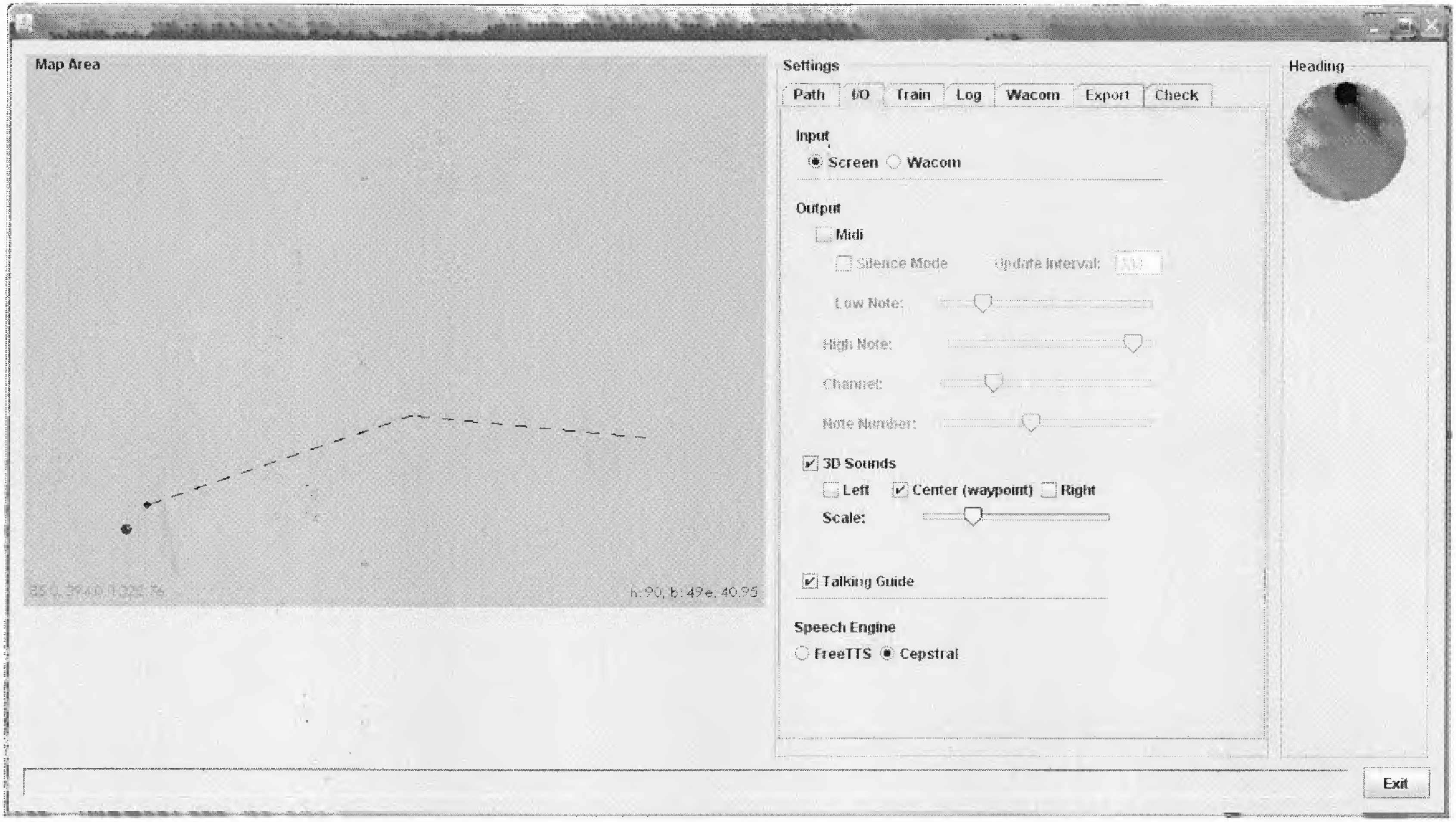
The user interface chosen needs to employ several sub-components. For the evaluation system, both audio and graphical interface components are needed. For prompts, the rendered audio needs to present both spoken words and non-speech audio sounds. To investigate spatialized displays (where a stimulus appears to be at a location), a 2d or 3d rendering capability is needed. Finally, a graphical console is needed for the investigator to administer experiment sessions. These subcomponents are discussed in detail below.

3.6.3.1 1D Audio Rendering Components. Companion research at NJIT into touch/speech browser interfaces provided significant benefit for the selection of components for "text-to-speech." In order to render text as speech, two technologies have been explored: (1) *FreeTTS* and (2) *Swift* from Cepstral. FreeTTS is a publicly available text-to-speech (TTS) processing library from Sun Microsystems. It provides medium quality rendering. Work in the NJIT AudioBrowser research group has shown that many users are not tolerant of low or medium quality solutions. As a result, a higher quality, commercial solution was integrated into the companion group's AudioBrowser project in addition to FreeTTS. Following their lead, the evaluation system provides interfaces to both Cepstral and FreeTTS. Cepstral has kindly donated the software license for Swift for use in this research. Swift is used as the exclusive TTS interface for work in the evaluation system going forward. FreeTTS is Java based and meets the platform neutrality goal; Swift is multiplatform but does not currently offer a binding to Java. A custom Java Native Interface (JNI) library was created to bridge from the developed evaluation system to Cepstral's libraries on the Microsoft Windows platform. This library has been shared with the vendor.

In addition to rendering spoken word, audio interfaces also commonly employ non-spoken sounds. The Java Media Framework (JMF) was selected for the display of all non-speech audio sounds.

3.6.3.2 2D/3D Audio Rendering Component. Cepstral's swift and JMF, both described in the previous section, are very good at providing both TTS and non-speech audio sounds. An additional audio rendering need still exists for the display of spatial information. Although JMF could be used to simulate a 3D environment, this would create a programming burden which has already been tackled elsewhere. Existing, publicly available solution libraries exist that model the physical characteristics of sound and allow the programmer to easily utilize sounds in a virtual 3D environment. Java 3D (http://java.sun.com/products/java-media/3D/) was evaluated and eliminated, due to documented weaknesses in the sound rendering capabilities. OpenAL (the Open Audio Library, http://www.openal.org) was adopted for the 2D and 3D audio rendering. A Java binding for OpenAL is available from https://joal.dev.java.net and was utilized to integrate OpenAL with the evaluation system.

3.6.3.3. Graphical User Interface Component. In addition to audio interface components, graphical components of the evaluation system must be provided for the investigator. These components implement the functionality to start and stop experiments, to select experiment settings, and to examine and export test data. Many standard toolkits exist for the construction of such interfaces. In keeping with established approach of building a platform neutral Java based application, Java's Swing library is used for creation of the graphical interface to the evaluation system. Additionally, the Matisse layout tools in the netbeans integrated development environment are used for rapid prototyping of user interface components.


Map Area
h: 90, b: 49e: 40.95
Settings
Path
I/O
Train
Log
Wacom
Export
Check
Heading
Exit

Input
● Screen ○ Wacom

Output
☐ Midi
☐ Silence Mode Update Interval:
Low Note:
High Note:
Channel:
Note Number:

☑ 3D Sounds
☐ Left ☑ Center (waypoint) ☐ Right
Scale:

☑ Talking Guide

Speech Engine
○ FreeTTS ● Cepstral

Figure 3.4 taux evaluation system as viewed from graphical user interface.

3.6.4 botGuide System

The final component for consideration is the botGuide. No known public tools or framework were found to support this need, so a "homegrown" implementation is provided as part of the evaluation system. This component is responsible for starting and stopping experiments, monitoring the subject's state during the experiment, and signaling events to interested observers as they happen. The botGuide also facilitates the retrieval, analysis and exporting of experiment data. To achieve platform neutrality, Java is chosen as the implementation language and underlying system. With its platform independence, object orientation and excellent multi-threading capability, Java is a good platform for integrating to the other subsystems. Building the evaluation system on a Java platform also supports the desired goals of future adaptation -- where a new location sensing system can be integrated or a new deployment platform (PDA, cell phone) can be easily accommodated.

The rationale for the subsystem selections has been provided. Next, an illustration is provided to show the interplay of the subsystems in a walk through of the evaluation system.

3.7 The Simplified Illustration, Revisited

In order to demonstrate the function of the selected subsystems, the following scenario is offered. This example will connect the components and tasks in the scaled, experimental environment with those of the initial *Illustrative Example*.

A volunteer subject sits in front of the tablet and puck device wearing a stereo headset. The investigator sits nearby, also wearing a headset and with the evaluation system console in view (see Figure 3.5).

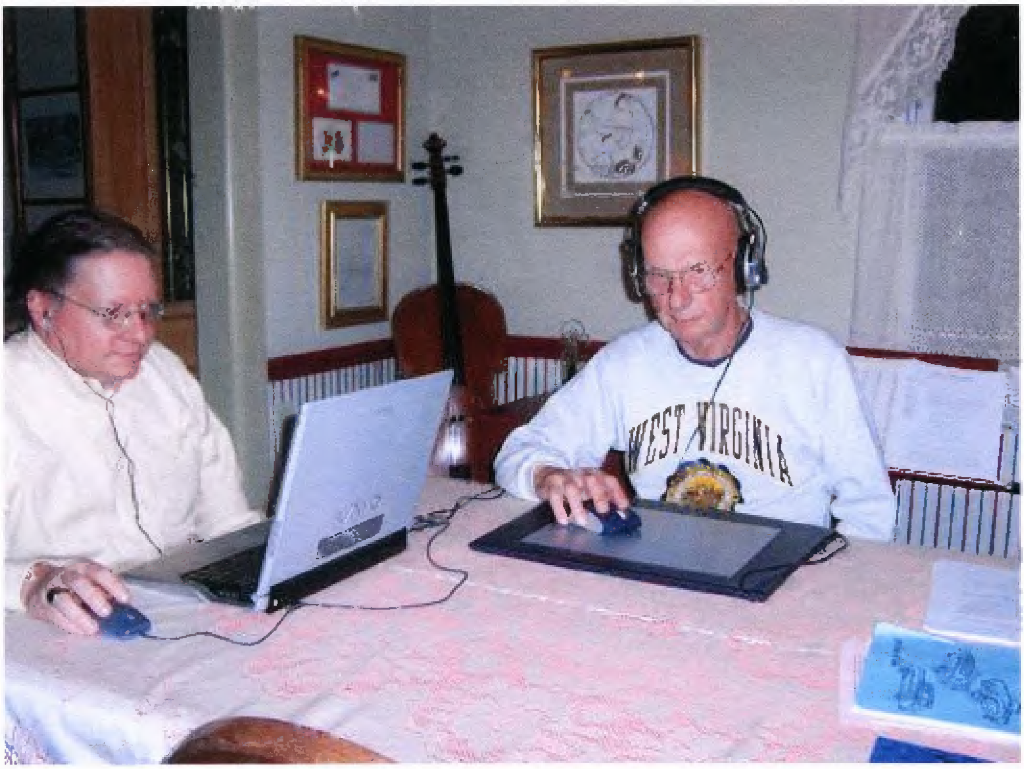
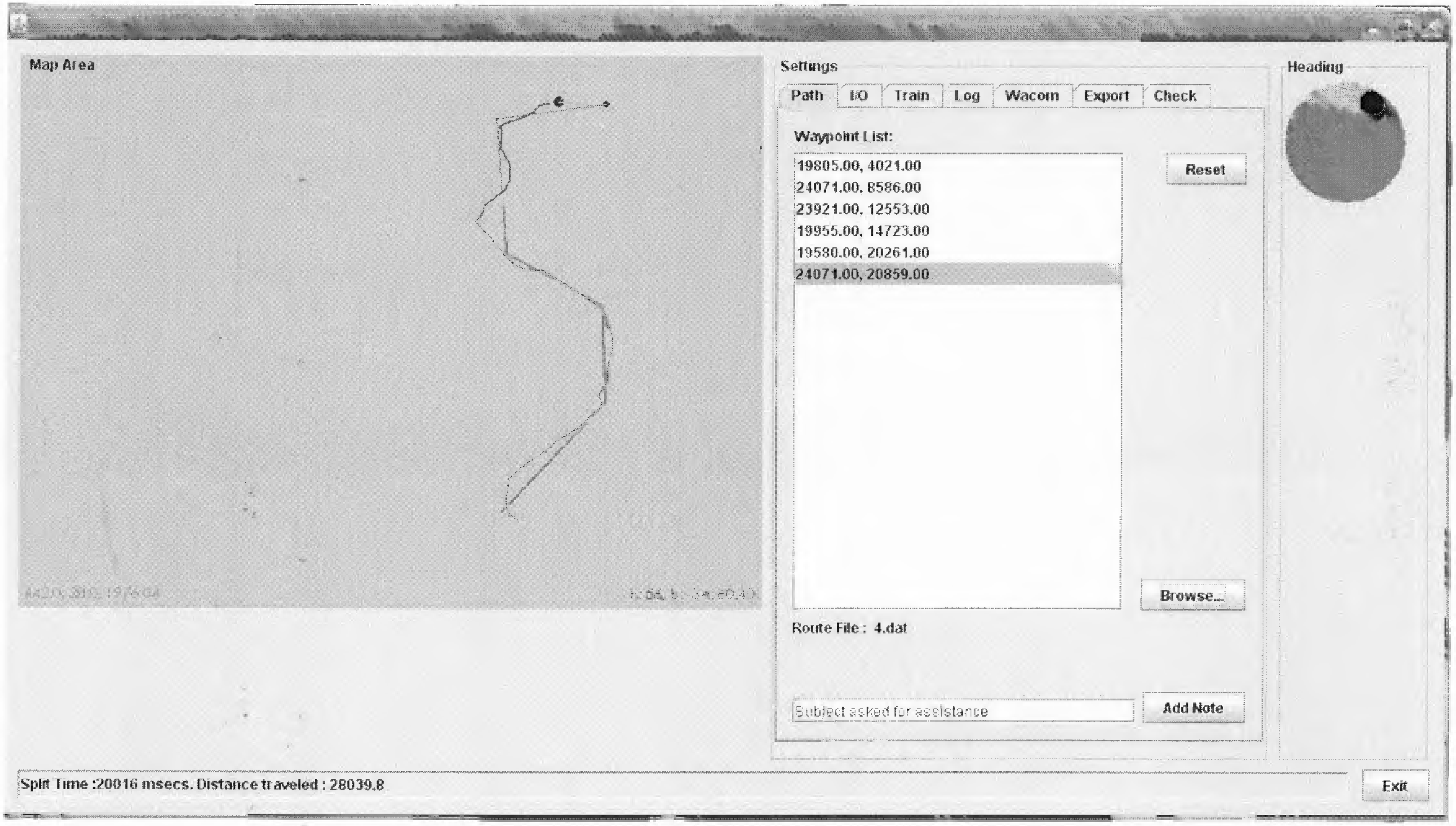


Figure 3.5 Investigator (left) views the evaluation system console while subject (right) follows the experimental protocol using the tablet and puck device.

The investigator reads instructions that help the subject (Don) understand the steps of the experiment and how to interpret the generated sound. Don will use this sound to progress through predefined destinations and complete a route on an invisible map projected onto the tablet. Don proceeds as follows. After performing practice exercises, he participates in a measured trial. The investigator accesses a pre-defined route and selects it for display via the tablet. Don hears feedback that identifies the route start point on the tablet; he navigates there following the generated sound. Once he arrives, a special sound is signaled to alert him of the arrival. The generated sound now changes to identify the next location in the route; Don navigates there based on the stimulus. Another arrival sound occurs; the generated sound is now updated to identify the next location. This process is repeated for 3 to 5 intermediate locations. A final sound pattern occurs to signal that the entire route navigation has completed. During the experiment, the evaluation system captures performance data for Don's travel. The system also provides graphical feedback of Don's travel to the investigator through the console. Figure 3.6 shows the investigator’s console.


Map Area
Settings
Path
I/O
Train
Log
Wacom
Export
Check
Reset
Browse...
Add Note
Heading
Exit

Waypoint List:
19805.00, 4021.00
24071.00, 8586.00
23921.00, 12553.00
19955.00, 14723.00
19580.00, 20261.00
24071.00, 20859.00

Route File : 4.dat

Subject asked for assistance

Split Time :20016 msecs. Distance traveled : 28039.8

Figure 3.6 Investigator's console, showing subject's progress.

Recall the earlier Illustrative Example, where a user navigated through city streets. You will see that many of the characteristics of that stylized environment are not present within the evaluation system. But, the main focus of investigation is preserved: the generated sound which represents navigational instruction and information for the navigator.

3.8 Problems Solved

During the early phases of the system development and pilot testing several problems were identified. Details about the solutions that address these problems will appear in the sections that follow. The main problems encountered are briefly summarized in this section as an aid to the reader. These break down into three categories: the experience, the tools/libraries and the experiment.

3.8.1 Experience

Work from companion research work at NJIT (Chen, Tremaine, Chung, Lutz & Lacsina, 2006) showed that users of auditory displays have a low tolerance for poor quality in speech rendering. As a result, and consistent with that companion research work, a high quality commercial text-to-speech application was integrated with the evaluation system. It is recognized that a future investigator may not wish to purchase a license for the higher quality text-to-speech rendering, so the initial support that was developed in the evaluation system for the free *FreeTTS* text-to-speech rendering library has been maintained.

3.8.2 Tools / Libraries

A robust environment needed to be developed or identified for the rendering of sound sources in 3D. Developing a homegrown solution seemed daunting and unproductive, since this capability has already been developed elsewhere. Adopting Java's Java 3D API seemed promising, but quickly revealed problems due to its immaturity. In a manner with that similar to the investigation with location sensing, other non-conventional approaches were pursued. By leveraging the work from a PC gaming consortium, a sturdy, proven, open source library was identified. taux is not alone in adopting OpenAL, it has also been used by Walker and Lindsay (2006) in their System for Wearable Audio Navigation, within its virtual environment for testing. The Open Audio Library (OpenAL) is provided as a series of Windows-based dynamic link libraries (DLLs), so an additional library – a java binding for OpenAL – was needed and is used for integration (https://joal.dev.java.net/).

Providing the capability to create and maintain a collection of spatial data sets for use in experiments was identified. Initially, it was easy to build and maintain these manually. As this research progressed, it was observed that it would be desirable to do this with some level of automation through an application rather than manually. Furthermore, it would be effective to plot a subject's paths graphically and possibly to superimpose data from different or data from different subjects onto the same plot. In order to support this bi-directional interface to a graphical environment, the capability would need to be developed. In order to add this capability without recreating mature solutions that already exist, the decision was made to integrate with an existing 2D drafting application.

Multiple coordinate systems are used in the evaluation system to describe the system and interface states. A strategy had to be developed to allow for transformation between coordinate systems and to maintain coherency of the multiple representations. The transformations had to be done efficiently and not hinder system performance. Classes and operations from Java3D's library are used to establish a global coordinate system and multiple local coordinate systems. The AffineTransformation class and its transformation methods are used to perform all required matrix algebra.

The tablet reporting frequency was found to create more data volume than was necessary to record a subject's progress. With a high volume of data, a risk exists that system resources will be exceeded or system performance will be adversely affected. Simply reducing the tablet sampling could have undesirable effects, where a corresponding latency would be introduced in the user interface. The Sampler class was introduced to decouple this downstream sampling need so that Sampler could run as its own process thread and specify its own reporting frequency. Setting the Sampler frequency independently allows for a coarser reporting frequency while maintaining the appropriate sampling frequency from the tablet for user interface operations.

3.8.3 Experiment

Four problem areas were identified in early trials. First, some subjects experienced disorientation during isolated instances when following a spatialized audio signal. Several root causes were suspected and investigated. These included: individual subject difficulties ("this feedback just doesn't work for *me*"), a bad audio headset, and even a suspected imbalance in hearing loss with one of the subjects. It turns out that, after investigation, there was a software defect. A narrow set of circumstances stimulated this failure mode. As a result of interim troubleshooting, a measurement process was incorporated to confirm that rendered audio level is always balanced across the headset. Even thought the headset was not faulty, it was replaced and the validation measure has been maintained.

Second, during practice and trials it became evident that subject's performance improves while they are becoming accustomed to a new display. At some point, they learn to use the feedback and this ‘learning’ improvement diminishes. Instrumentation was added to the evaluation system to capture, aggregate and record performance measures while they are underway. The solution was not completely successful; this will be discussed in detail later in the Discussion of Results section.

Third, during initial trials, exceptional events were difficult to correlate to the timeline of an actual experiment. As an example, a phone might ring or a visitor drops into the room where the experiment is conducted. These events were being noted on an investigator worksheet, but it was suggested that these events could also be recorded by the evaluations system using its timeline. A capability to attach arbitrary notes with timestamps was added to the evaluation system.

Fourth, during trials, two difficulties were experienced in dealing with tablet boundaries. If a subject wandered outside of the tablet boundary, the displayed audio feedback wouldn't change and the subject would not realize they have crossed the tablet boundary. The subjects became disoriented. Additionally, between trials, the subjects were instructed to bring the puck back to the bottom center of the tablet. Without a discreet registration point, there was variability in the starting location for the next task. To remedy this, logic was added to signal the out of bounds condition and a physical fixture was added to the tablet to identify the home location.

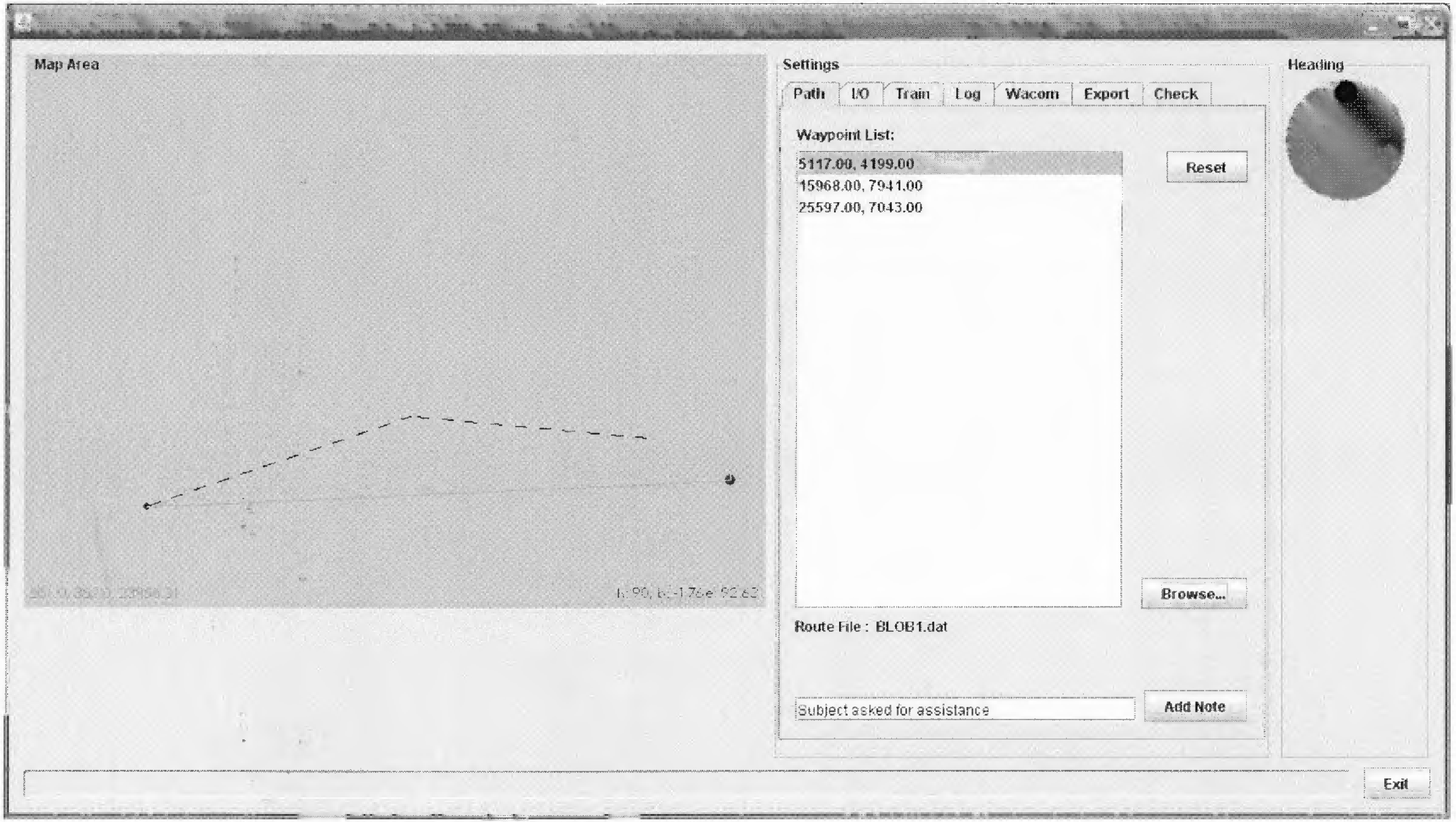
This section summarized solutions that were found regarding the experience, the tools/libraries used and the experiment process in early evaluation system work. Additional discussion and rationale will appear in the sections that follow.

3.9 Basic System Operation

This section describes how an investigator would use the evaluation system to perform an inquiry of their own. This path could be followed for either structured experiments or for ad-hoc investigations.

First the investigator needs to follow the instructions outlined in the Physical View section. This will help identify, install and configure the hardware and software components needed for a fully functioning evaluation system.

Once the evaluation system is running, the investigator needs to identify the route data to be used. The route data file is selected from the Path tab within the tool (Figure 3.7). By default there are 5 sets of experiment data (named A0,A1,A2,B1,B2) and one set for practice sessions (named *training*). These can be selected by selecting the *Browse...* button within the Path tab. Figure 3.8 shows the arrangement of directories holding data for multiple experiment conditions, Figure 3.9 shows the contents of a data directory.


Map Area
Settings
Path
I/O
Train
Log
Wacom
Export
Check
Heading
Reset
Browse...
Add Note
Exit

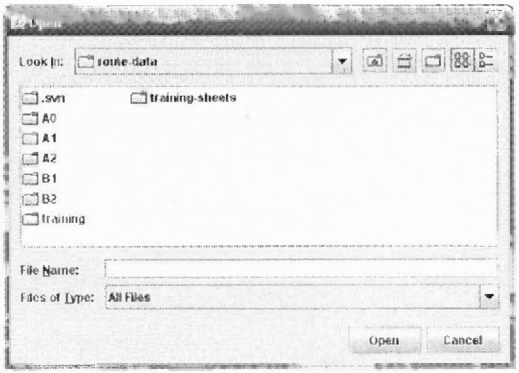
Waypoint List:

5117.00, 4199.00
15968.00, 7941.00
25597.00, 7043.00

Route File : BLOB1.dat

Subject asked for assistance

Figure 3.7 Path tab on evaluation system console.



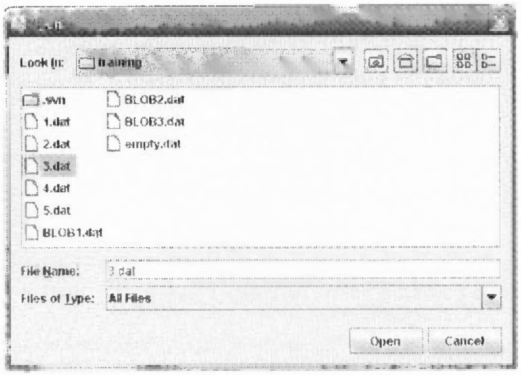
Look In: route-data

File Name:

Files of Type: All Files

.svn
training-sheets
A0
A1
A2
B1
B2
training
Open
Cancel

Figure 3.8 Directory structure for route data



Look In: training

File Name: 3.dat

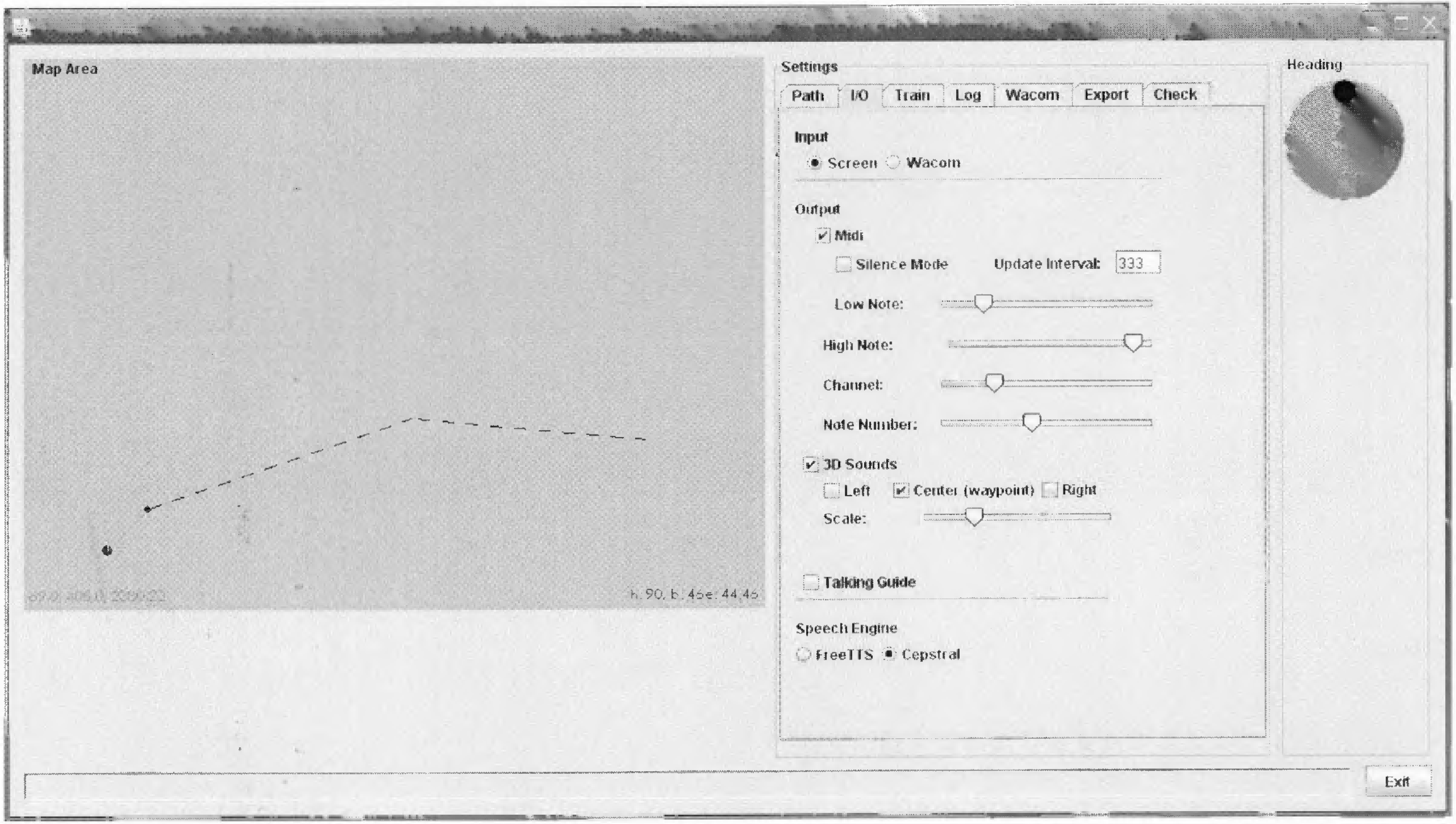
Files of Type: All Files

.svn
BLOB2.dat
1.dat
BLOB3.dat
2.dat
empty.dat
3.dat
4.dat
5.dat
BLOB1.dat
Open
Cancel

Figure 3.9 Contents of directory with route data for a condition

Once the intended route data has been selected, the investigator describes the attributes of the audio display. These selections are made with under the I/O tab of the evaluation system (see Figure 3.10). Several display modes are possible: Midi, 3D sounds and Talking Guide. These are not exclusive options, they can be mixed and matched and desired. New displays could also be developed, incorporated, and mixed as well. Once the investigator has made their selections, they are ready to begin a training or trial session with the subject.

Prior to running any trials, the investigator will want to perform orientation and training with the subject. To aid in these steps, a tabbed panel is added to the evaluation system and labeled 'Train.' This panel is used to stimulate system messages during training (Figure 3.11).


Map Area
h: 90, b: 45e: 44.46
Settings
Path
I/O
Train
Log
Wacom
Export
Check
Heading
Exit

Input

● Screen ○ Wacom

Output

☑ Midi

☐ Silence Mode Update Interval: 333

Low Note:

High Note:

Channel:

Note Number:

☑ 3D Sounds

☐ Left ☑ Center (waypoint) ☐ Right

Scale:

☐ Talking Guide

Speech Engine

○ FreeTTS ● Cepstral

Figure 3.10 I/O tab of the evaluation system.

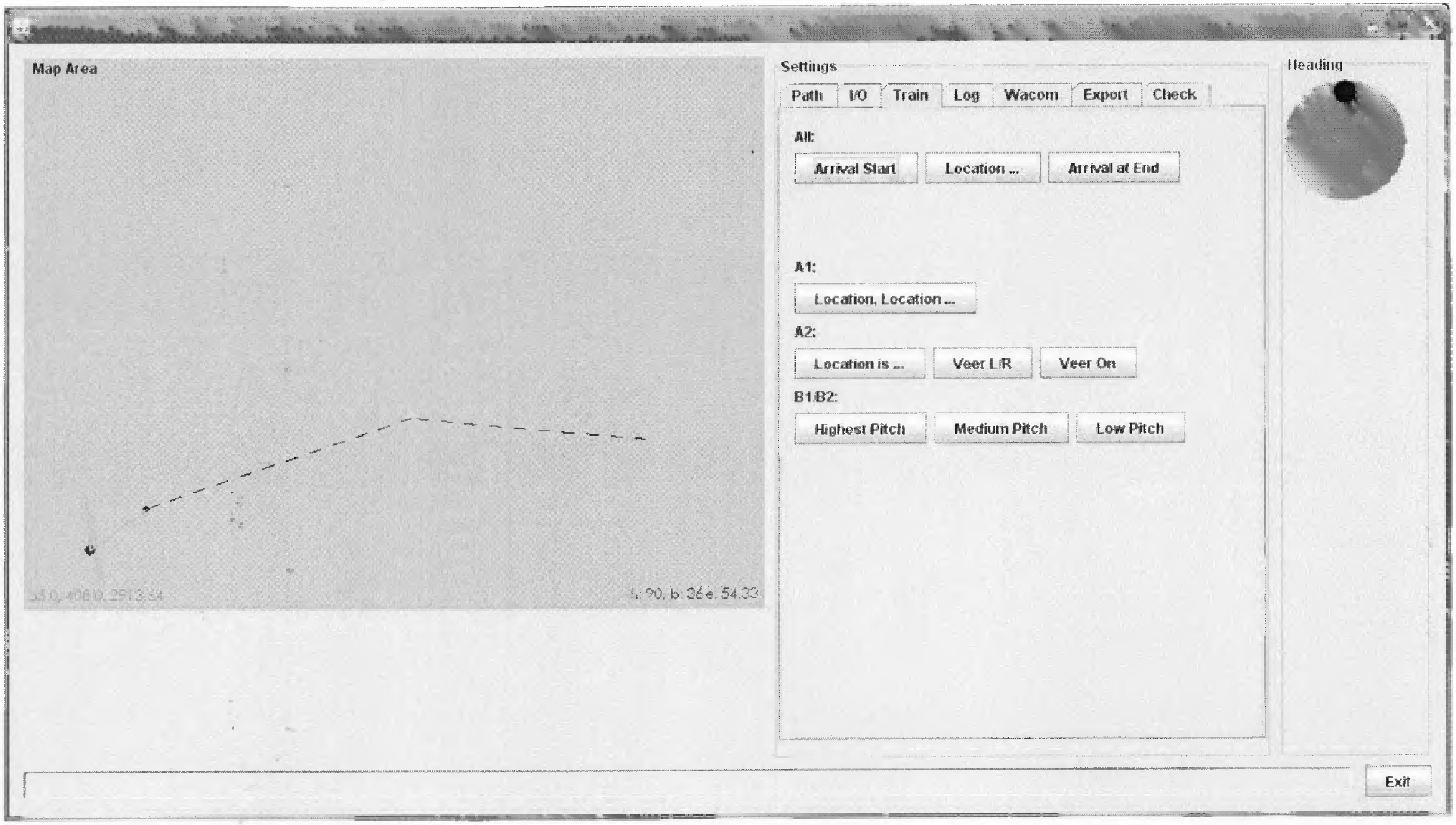

Map Area
h: 90, b: 36 e: 54.33
Settings
Path
I/O
Train
Log
Wacom
Export
Check
All:
Arrival Start
Location ...
Arrival at End
A1:
Location, Location ...
A2:
Location is ...
Veer L/R
Veer On
B1B2:
Highest Pitch
Medium Pitch
Low Pitch
Heading
Exit

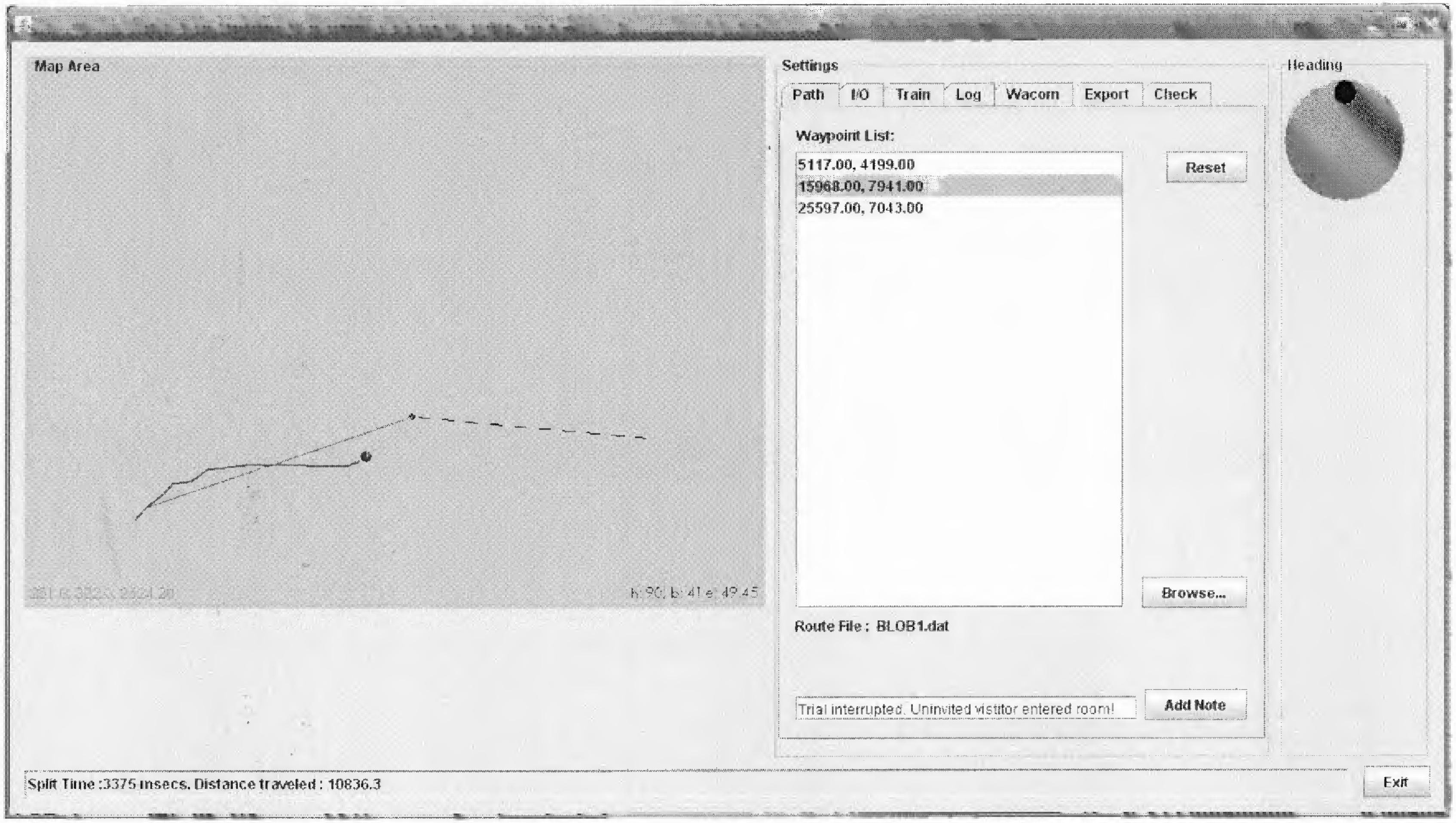
Figure 3.11 ‘Train’ tab within the evaluation system.

After training, the investigator is ready to begin a trial. He instructs the subject to begin. The subject follows the auditory display, navigating from waypoint to waypoint. The performance data is recorded once the subject reached the start point of the route, and is collected until the subject reaches the finish point. There are no actions that the investigator needs to take during this process.

While navigation is proceeding, an investigator can optionally introduce an investigator's note. At times, during an experiment, exceptional events occur. These can be recorded on an investigator's worksheet, but this method may not be as efficient as recording them within the evaluation system itself. When recording with the evaluation system, the messages are time stamped and recorded along with the experiment data alleviating the burden of synchronizing them later (see Figure 3.12). The note is added in the text field near the bottom of the Path tab, the note is committed by selecting the Add Note button.

Once the trial has been completed, the investigator needs to commit the data to a disk file. This is done from the Export tab (see Figure 3.13). The investigator adds the subject's name or subject ID into the Subject field. Selecting the Export button near the bottom of the tabbed panel will commit the data to a disk file.

The basic operation of the system has been described: starting the system, loading route data, setting display properties, performing the training, adding investigator's notes and exporting the trial data. The next section will examine the evaluation system in detail.


Map Area
h:90, b:41 e:49.45
Settings
Path
I/O
Train
Log
Wacom
Export
Check
Heading
Reset
Browse...
Add Note
Exit

Waypoint List:

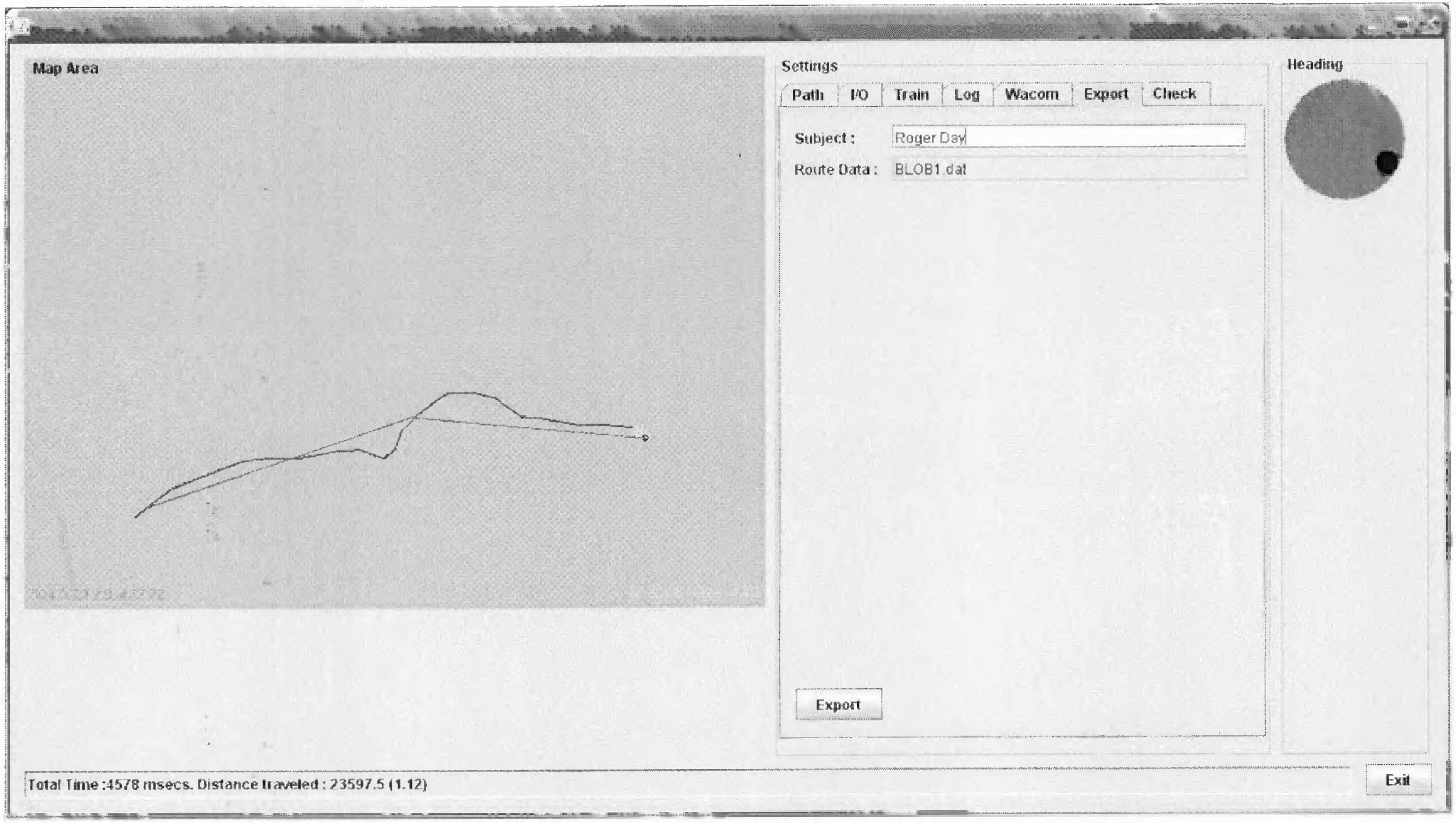
5117.00, 4199.00
15968.00, 7941.00
25597.00, 7043.00

Route File : BLOB1.dat

Trial interrupted. Uninvited visitor entered room!

Split Time :3375 msecs. Distance traveled : 10836.3

Figure 3.12 Adding an investigator's note during a trial.


Map Area
Settings
Path
I/O
Train
Log
Wacom
Export
Check
Heading
Export
Exit

Subject : Roger Day

Route Data : BLOB1.dat

Total Time :4578 msecs. Distance traveled : 23597.5 (1.12)

Figure 3.13 Exporting trial data.

3.10 Detailed System Description

The following section presents a methodology and related justification for presenting a detailed description of the evaluation system. In order to describe the evaluation system, a formal notation will be utilized. A standard notation for software and systems development is the Unified Modeling Language, or UML. Since it is recognized that some readers may not be familiar with UML, appropriate commentary will be provided to establish context and notations. Support for the selection of the artifacts is also provided.

UML can be used to define a system at varying levels of detail. At one extreme, systems can be described at a very fine resolution. These descriptions are analogous to blueprints and offer enough detail to fully implement the desired system. In most extreme cases, the blueprints express a language which can be automatically manifest as a system implementation. At the other end, systems can be described at a much higher conceptual level with the detail levels omitted. This approach follows the advice of Fowler's 'UML as a Sketch' (UmlAsSketch, 2007) and contemporary *agile* development methods. For the purposes of this work, the system will be described at a conceptual level with increased detail in selected areas where additional emphasis is helpful.

UML provides a rich set of artifacts and constructs for a systems description. Simply presented in bulk, these items can be confusing. Philipe Kruchten (1996) suggests a model for describing a system architecture as multiple concurrent views. These views each represent a particular set of concerns. The views are divided into 5 sets: Use Case View, Logical View, Physical View, Process View and Development View (Figure 3.14).

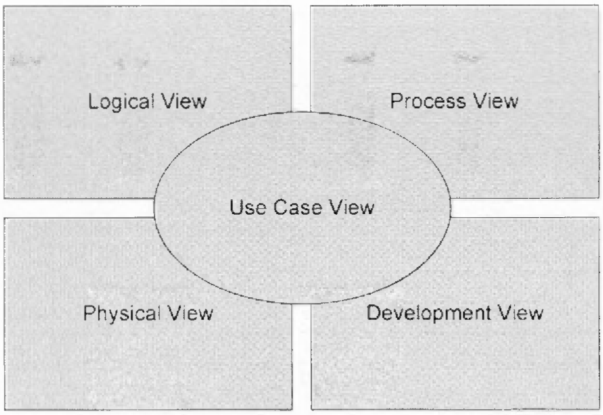

Logical View
Process View
Use Case View
Physical View
Development View

Figure 3.14 Philipe Kruchten's 4+1 view model of software architecture.

Hamilton and Miles (2006) offer a mapping of Kruchten's model for UML 2.0 artifacts. This mapping will be utilized in the following system description to populate the various views with appropriate UML 2.0 constructs.

This introduction provided Kruchten's 4+1 and UML as a model and a notation for a system description. The next several sections will dive into each of the system views and provide description of the related concern using artifacts from the UML standard notation following Krutchen's 4+1 Model.

3.10.1 Use Case View

Following Krutchen's 4+1 model, The Use Case View is considered first (Figure 3.15).

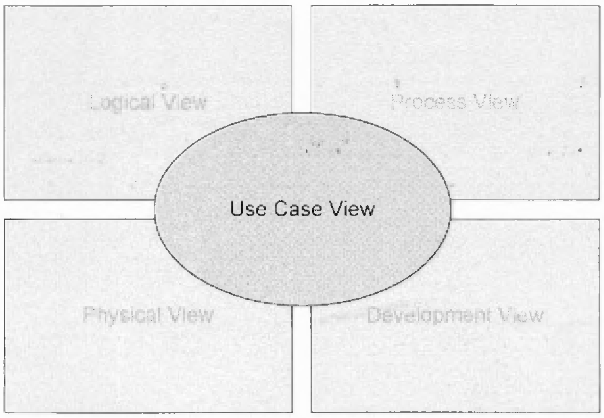

Logical View
Process View
Use Case View
Physical View
Development View

Figure 3.15 Kruchten's 4+1, the use case view.

Use cases are widely discussed in the literature; many definitions exist. For purposes of this work, Hamilton and Miles' (2006) description is used: "A use case is a case (or situation) where your system is used to fulfill one or more of your user's requirements; a use case captures a piece of functionality that the system provides." Referring back to the 4+1 model, it is readily observed that the use cases interact with all of the other system views. Given its overarching status, and the strong linkage back to the system's requirements, it makes sense to begin the description by expanding on the uses cases first.

Use cases consist of relationships: between system users (actors) and the operations that they perform (actions). Figure 3.16 depicts all of the actors and the primary actions supported by the system.

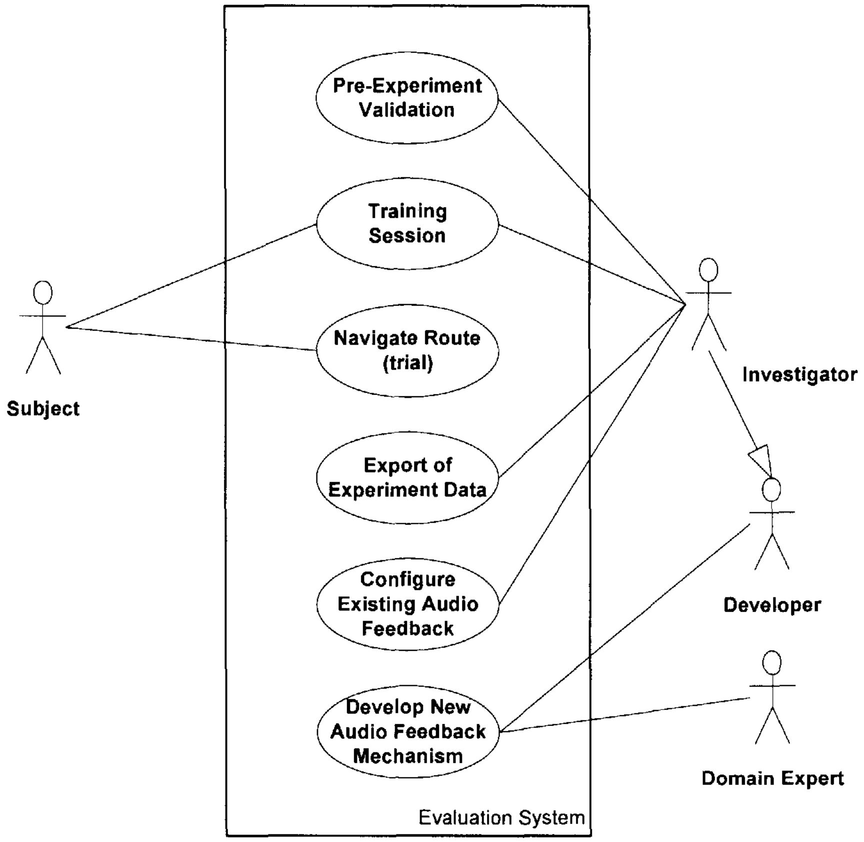

Pre-Experiment Validation
Training Session
Navigate Route (trial)
Export of Experiment Data
Configure Existing Audio Feedback
Develop New Audio Feedback Mechanism
Evaluation System
Subject
Investigator
Developer
Domain Expert

Figure 3.16 Evaluation system use case diagram.

As previously stated, the use case diagram is a tool that describes the system's use and the fulfillment of the original system requirements. The tables in Appendix O provide the additional detail for each use case. This detail completes the description for each use case.

3.10.2 Process View

The previous section described the primary Use Cases View for the system. The next view to consider is the Process View.

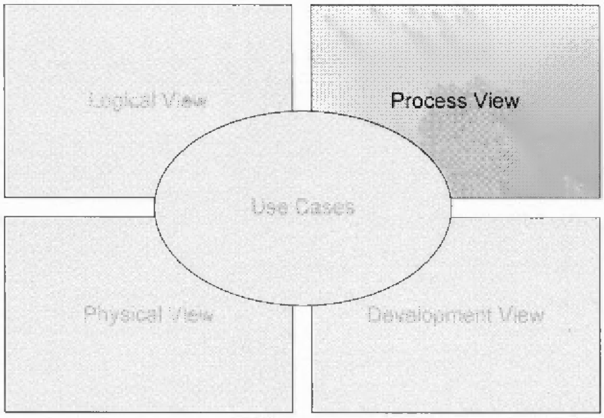


Figure 3.17 Kruchten's 4+1: process view.

The process view considers overall system processing from a lifecycle perspective – how the system gets from its beginning to ending states. Since the system has a requirement to provide feedback with perceived real time performance (requirement A.3), and since multiple information displays (audio, graphical, data samplers, etc.) will be active simultaneously, multiple processes will need to run in the system in a parallel fashion. To support this requirement, multiple 'threads' of execution will need to run concurrently. This need is implemented by using a multi-threaded environment. The process flows, expressed with UML's activity diagrams, are shown in this section to illustrate the logic of the parallel execution paths. First, an overall view of the system is presented in Figure 3.18.

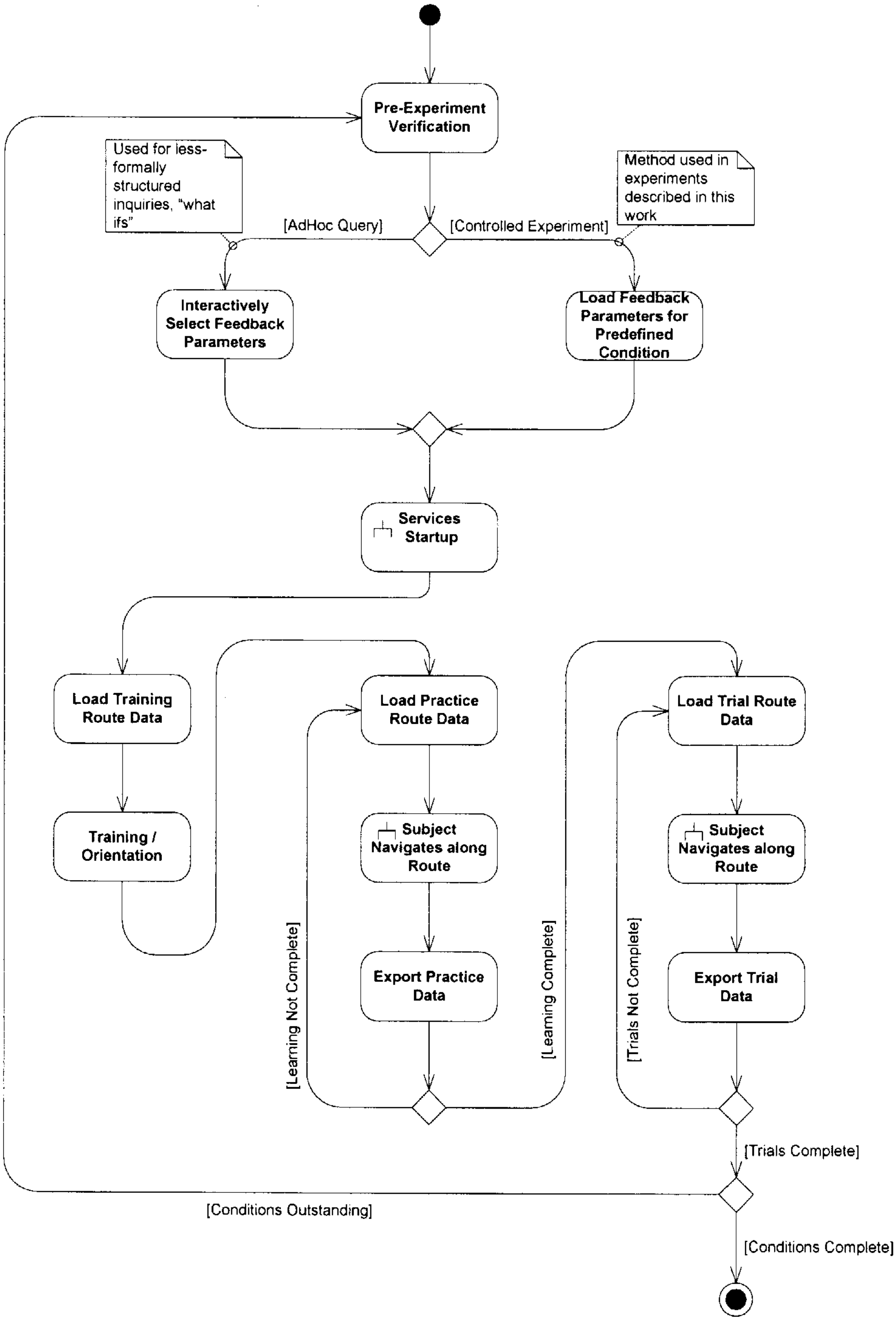

Pre-Experiment Verification
Used for less-formally structured inquiries, "what ifs"
Method used in experiments described in this work
[AdHoc Query]
[Controlled Experiment]
Interactively Select Feedback Parameters
Load Feedback Parameters for Predefined Condition
Services Startup
Load Training Route Data
Training / Orientation
Load Practice Route Data
Subject Navigates along Route
Export Practice Data
[Learning Not Complete]
[Learning Complete]
Load Trial Route Data
Subject Navigates along Route
Export Trial Data
[Trials Not Complete]
[Trials Complete]
[Conditions Outstanding]
[Conditions Complete]

Figure 3.18 Main process activity diagram.

UML's activity diagrams use several symbols and notations. The process start and end point are identified with circles: a single filled circle at the start and a filled circle with a surrounding ring at the end. Actions are represented with rounded boxes, and the transitions between them are connected by paths (or edges). Arrowheads are used on the paths to describe the direction of the process flow from action to action. Decision points, similar to those familiar on flow charts, are depicted with diamonds. Guard conditions, or those words and phrases along the edges near the decision points, describe the condition under which the activity will take that branch. Finally, the symbol that looks like a stylized organization chart describes an action that is more complex and can be more fully described as a subsystem. The 'Services Startup' subsystem and the 'Subject Navigates Along Route' subsystem activity diagrams appear subsequently in this section.

Following the main activity diagram from the start point, it is seen that an initial branching occurs. If this investigation is not structured, then the activity will progress down the left side. But, if this is an instance of a controlled experiment, it will progress down the right side. Once the independent selections are made on either branch, the activity then merges back and follows common path. Next, based on the displays that were selected and configured in that first branching, parallel processes will be started to service these requests. This startup process, labeled 'Services Startup' on the figure, will be performed next.

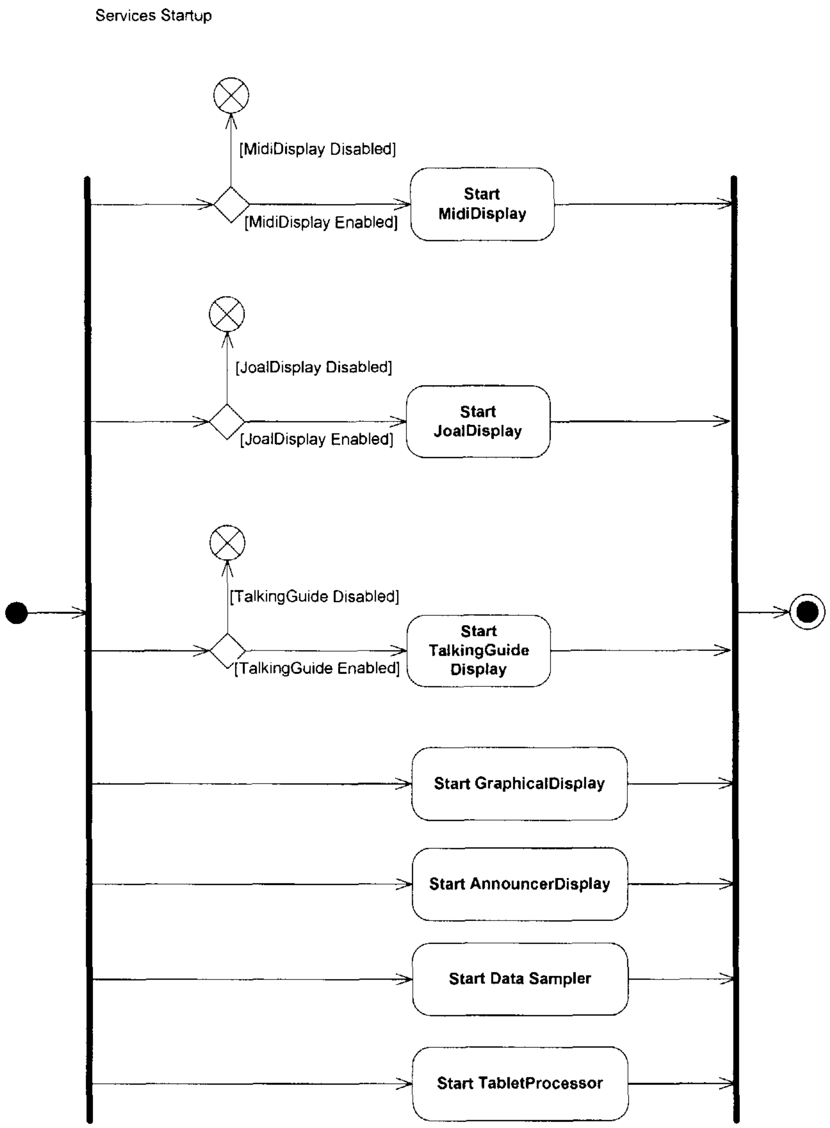
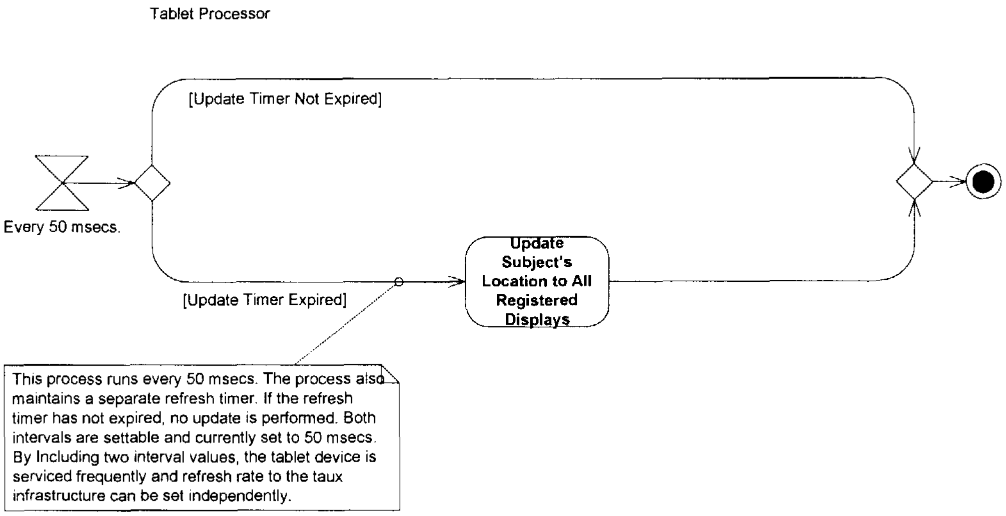

Services Startup
[MidiDisplay Disabled]
[MidiDisplay Enabled]
Start MidiDisplay
[JoalDisplay Disabled]
[JoalDisplay Enabled]
Start JoalDisplay
[TalkingGuide Disabled]
[TalkingGuide Enabled]
Start TalkingGuide Display
Start GraphicalDisplay
Start AnnouncerDisplay
Start Data Sampler
Start TabletProcessor

Figure 3.19 Services startup activity diagram.

The services startup activity diagram (Figure 3.19) introduces a new notation symbol. The vertical bars at the left and right of the diagram define bound processes that are started and run in parallel. In the figure, it is seen that the first three sub-processes (MidiDisplay, JoalDisplay and TalkingGuideDisplay specifically) are only started conditionally. These are started if they were enabled in the previous 'feedback parameter selection' step. The remaining four processes are always started.

The following sections will provide further detail about each sub-process and which of the system capabilities it provides. There are two fundamental classes of processes used: data producers and data consumers. In the current evaluation system, there is one data producer (TabletProcessor) and multiple data consumers. The consumers are: GraphicalDisplay, JoalDisplay, MidiDisplay, TalkingGuideDisplay, AnnouncerDisplay and DataSampler.

3.10.2.1.1 Tablet Processor Sub-Process. This process continuously monitors for subject location information and will inform all interested processes of any updates. Another new symbol is introduced here: an egg timer. This is the bowtie shaped graphic appearing in Figure 3.20. This symbol, when found on a UML activity diagram, represents a system delay. When the symbol appears without an incoming path (no arrow pointing towards it), this represents a process which runs periodically and wakes up at an interval described in the attached label. In this case, TabletProcessor will spring to life after 50 milliseconds of downtime since a prior execution. It will then follow the flow as described in the subsequent paths. In this case, the flow is relatively simple. The flow enters a branch and determines if a separate update timer has expired. If it has, the new location information is provided to all interested processes. I if not, this thread simply goes back to sleep. The decision to maintain two timers for this process is a conscious and deliberate one. Please see the note in the activity diagram (Figure 3.20) for a more detailed rationale.


Tablet Processor
[Update Timer Not Expired]
Every 50 msecs.
[Update Timer Expired]
Update Subject's Location to All Registered Displays

This process runs every 50 msecs. The process also maintains a separate refresh timer. If the refresh timer has not expired, no update is performed. Both intervals are settable and currently set to 50 msecs. By Including two interval values, the tablet device is serviced frequently and refresh rate to the taux infrastructure can be set independently.

Figure 3.20 TabletProcessor activity diagram.

3.10.2.1.2 AnnouncerDisplay Sub-Process. As shown earlier (Figure 3.19), the AnnouncerDisplay is always started. The AnnouncerDisplay provides speech output to inform the navigator when one of several events occur. These events are raised when a subject has (1) reached the route start point, (2) reached the route end point, (3) reached a route's intermediate point, (4) gone out of bounds or (5) received a signal that the route has been reset. The AnnouncerDisplay could also react to a subject location change event. Since there is no reasonable action for the AnnouncerDisplay process to take for this event, it is currently ignored.

The activity diagram for AnnouncerDisplay appears below as Figure 3.21. All of the events described above are represented in the activity diagram. As in the case of the TabletProcessor, the initial timer symbol shows that this process runs periodically (after 20 milliseconds of inactivity in this case). During this processing, any incoming events that have been queued will be processed. In the case of a subject location update, no action is taken. This is depicted with an edge that connects directly with the process end state. This condition and edge are not really necessary; these are included here for completeness. In the activity diagrams that follow this one, ignored conditions will not be shown. The other branches after the initial decision point are a bit more interesting. In the cases of route start and route end, 3 bells are signaled and a speech announcement is provided. When an intermediate route point has been reached, a single bell and an announcement are displayed. And finally, an announcement is provided if the user has gone out of bounds or the investigator has reset the navigation path back to the initial state. All these conditions are depicted by their respective paths on the activity diagram.

As a brief aside, this AnnouncerDisplay activity diagram is a very good example for the investigator to follow when building a completely new display. Construction of new displays will be discussed in more detail in the *Advanced System Operation* section that follows.

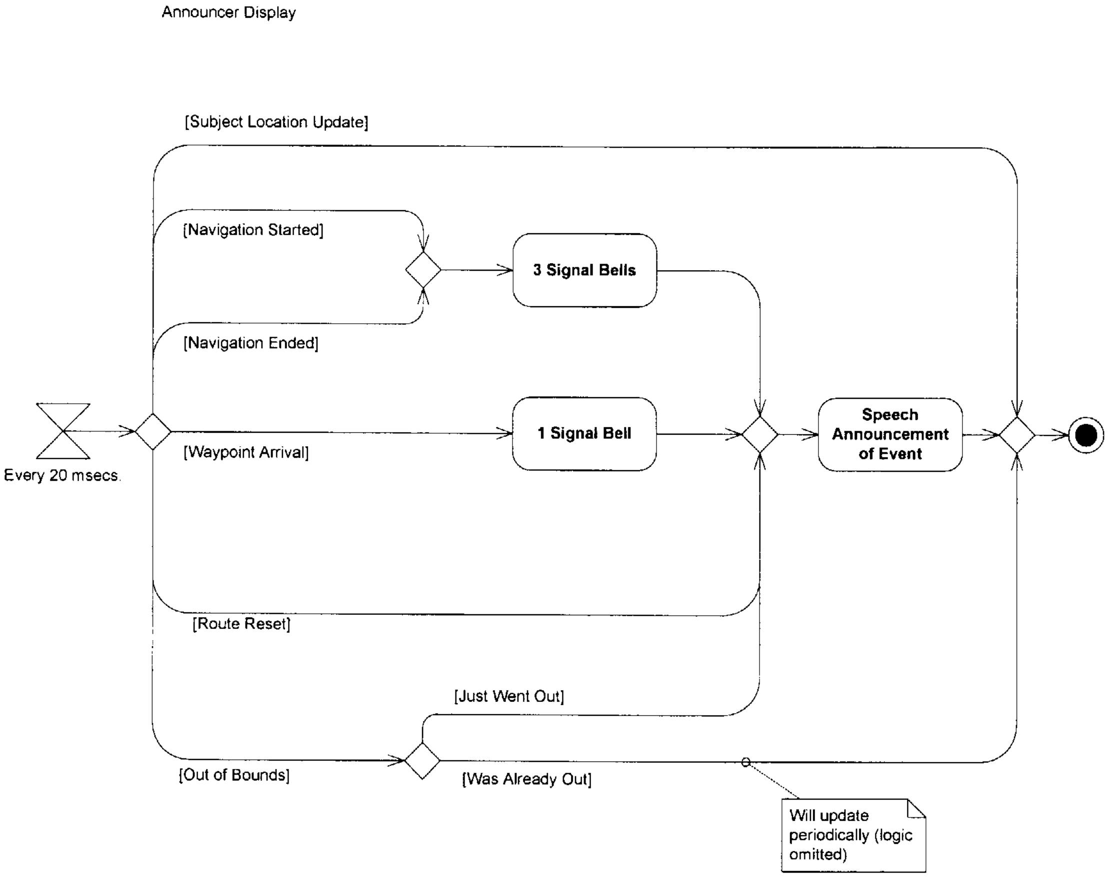

Announcer Display
[Subject Location Update]
[Navigation Started]
3 Signal Bells
[Navigation Ended]
Every 20 msecs.
[Waypoint Arrival]
1 Signal Bell
Speech Announcement of Event
[Route Reset]
[Just Went Out]
[Out of Bounds]
[Was Already Out]
Will update periodically (logic omitted)

Figure 3.21 AnnouncerDisplay activity diagram.

3.10.2.1.3 JOALDisplay (3D Audio Display) Sub-Process. The sub-process for JOALDisplay will only be started when the investigator calls for the display of 3D spatialized sound during the 'feedback parameter settings' action. This sound mechanism is used when an experimental condition is selected that provides the projection of a sound from an intended location.

As with previous displays, this sub-process schedules itself to run on a periodic basis. The process will run after every 20 milliseconds of inactivity. During processing, any incoming events that have been queued will be processed.

The 3D audio environment used is provided by OPenAL (www.openAL.org). From their website: "OpenAL is a cross-platform 3D audio API appropriate for use with gaming applications and many other types of audio applications." OpenAL supports sources positioning, reverberation, decay and Doppler effects. OpenAL offers c/c++ bindings for multiple platforms, but does not provide a Java binding. Since the evaluation system is built with Java, an additional component is necessary. The Java binding for OpenAL API (JOAL) was used. (https://joal.dev.java.net/)

As in the TabletProcessor and AnnouncerDisplay, this sub-process runs periodically. It responds to two event conditions: a changing of environmental settings and a subject location update. If environmental settings for related parameters change, such as enabling/disabling the sound beacon or changing the scaling of the virtual 3D sounds environment, the event is received and this sub-process adapts itself accordingly. Additionally, if a subject location changes, an event is received and this sub-process will make the corresponding adjustments. There is actually a third event of interest, the changing of a waypoint. Since this status change is already included within the periodic subject-location update event, it is not explicitly processed as a unique event. In the

JOALDisplay activity diagram (Figure 3.22), events that are not acted upon are not shown.

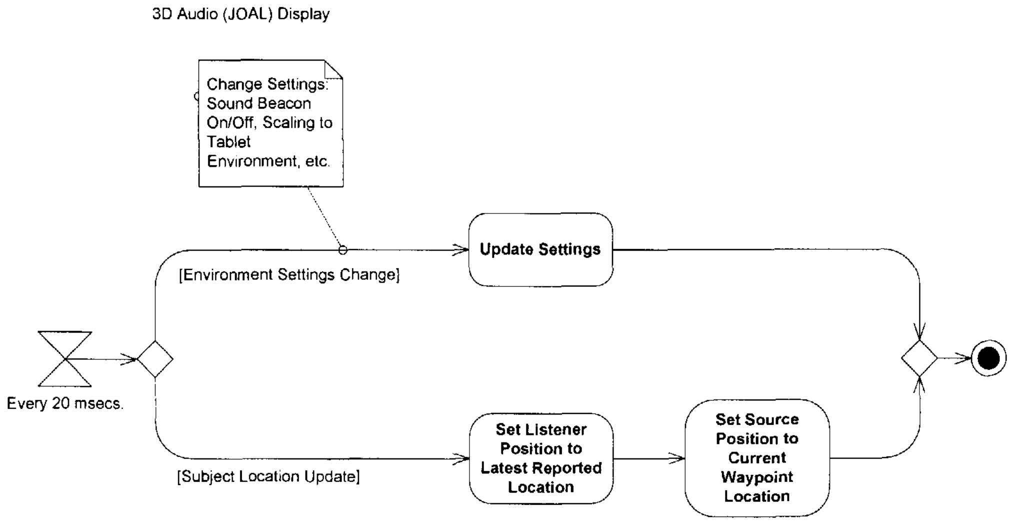

3D Audio (JOAL) Display
Change Settings: Sound Beacon On/Off, Scaling to Tablet Environment, etc.
[Environment Settings Change]
Update Settings
Every 20 msecs.
[Subject Location Update]
Set Listener Position to Latest Reported Location
Set Source Position to Current Waypoint Location

Figure 3.22 JOALDisplay activity diagram.

3.10.2.1.4 TalkingGuide Display Sub-Process. The sub-process for the TalkingGuideDisplay will only be started when the investigator calls for the 'Talking Guide' option during the 'feedback parameter settings' action in the main process flow. This sound mechanism is used when the experimental condition is selected that allows spoken hints during travel.

As with previous displays, this sub-process schedules itself to run on a periodic basis. During this processing, any incoming events that have been queued will be processed. The TalkingGuideDisplay supports two main modes: *New Destination* and *Destination Unchanged.* These are identified by the corresponding guard conditions of the same names in Figure 3.23. Initially, at the beginning of route navigation, the subject will not have any idea about where the next location is. The TalkingGuide will provide hints, on a periodic basis, informing the traveler that the destination is either to their left or to their right, and if the destination is in front of or in back of them. Once they become directed at the destination, the condition changes to *Destination Unchanged* and will remain that way until arrival at the next destination.

During the following period, where the guard condition remains at *Destination Unchanged*, two outcomes are possible. If the subject wanders off course, a spoken hint is provided directing them back to a correct heading. If they fail to return to course, and a time threshold is exceeded, an additional spoken hint is provided. This process continues until they return to course. Once they have corrected their course, the subject receives a spoken "O.K." message. Once the subject arrives at the next destination, the guard condition is updated to reflect *New Destination* again.

As before, while *New Destination* is active, the subject will receive hints with left/right and front/back guidance. Once the subject acquires an acceptable heading the mode is changed to *Destination Unchanged.* The entire process repeats until the route is completed, at which time the TalkingGuideDisplay does not process any events until a new navigation is started.

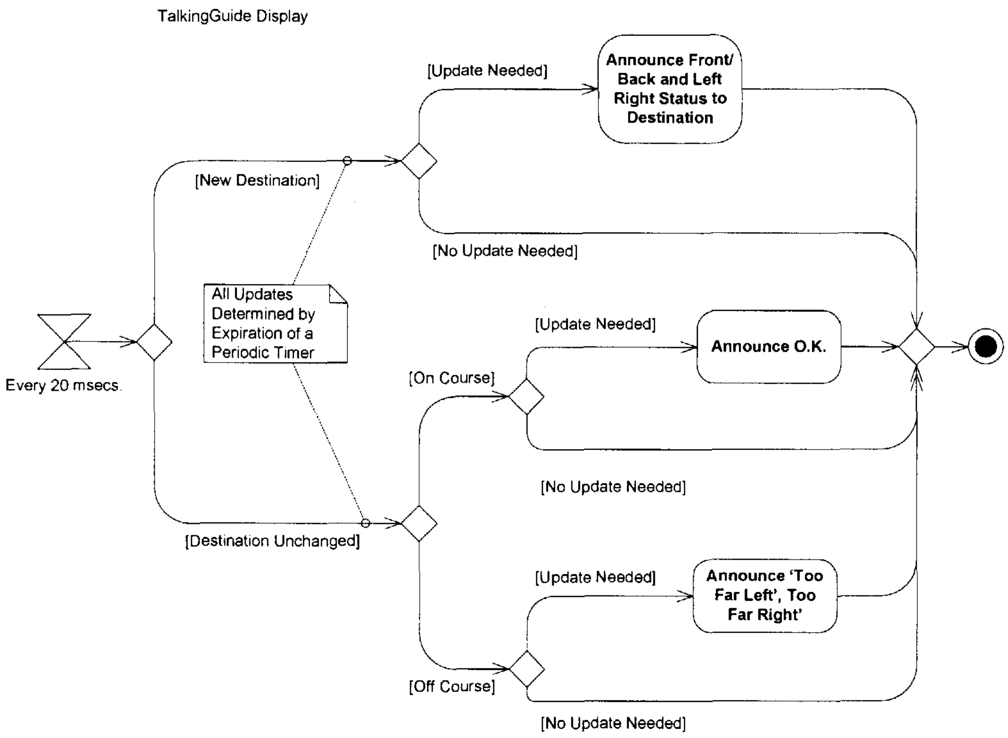

TalkingGuide Display
[Update Needed]
Announce Front/ Back and Left Right Status to Destination
[New Destination]
[No Update Needed]
All Updates Determined by Expiration of a Periodic Timer
[Update Needed]
Announce O.K.
Every 20 msecs
[On Course]
[No Update Needed]
[Destination Unchanged]
[Update Needed]
Announce 'Too Far Left', Too Far Right'
[Off Course]
[No Update Needed]

Figure 3.23 TalkingGuideDisplay activity diagram.

3.10.2.1.5 MIDIDisplay Sub-Process. The sub-process for MidiDisplay will only be started when the investigator calls for the 'Midi' output option during the 'feedback parameter settings' action in the main process flow. This sound mechanism is used when an experimental condition is selected that presents tones which vary to represent the navigator's heading error.

As with previous displays, this sub-process schedules itself to run on a periodic basis. During this processing, any incoming events that have been queued will be processed.

Tone generation is accomplished by calling the Musical Instrument Digital Interface (MIDI). The MIDI doesn't actually generate an audio signal, but provides a definition of a musical event that specifies the pitch, intensity and timing of a musical note. Within the evaluation framework, these events are generated and sent to the JavaSound application programming interface (Javasound API). This interface provides the implementation that performs the synthesis and sequencing of the MIDI event instructions requested. The JavaSound implementation schedules these audio events on the resident audio processing hardware.

The MidiDisplay sub-process responds to two events. The first is signaled to change the operation parameters (*environment settings change*): the note range, update frequency, instrument selection, and on-target reporting mode (sound v. silence). The second event type is a *subject positioning update*. These are both identified in Figure 3.24 as the initial guard conditions.

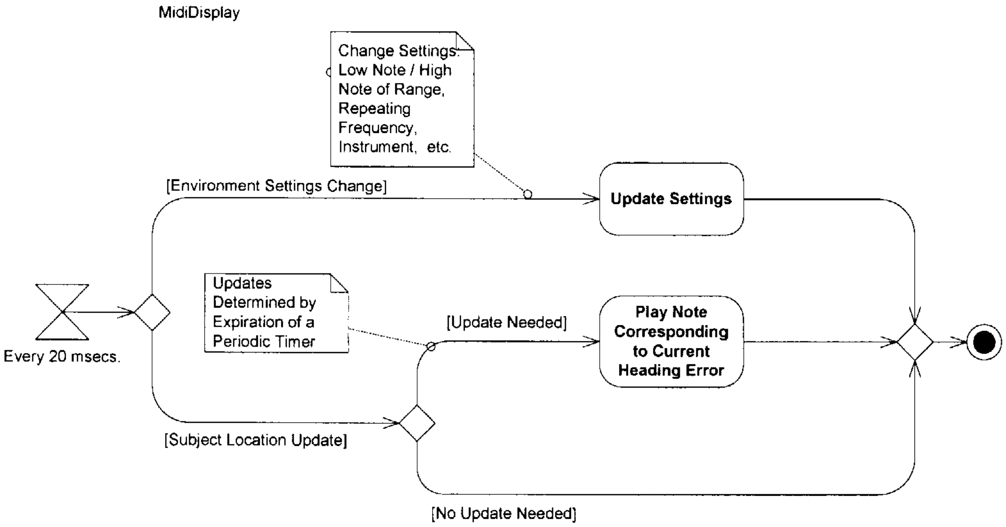

MidiDisplay
Change Settings: Low Note / High Note of Range, Repeating Frequency, Instrument, etc.
[Environment Settings Change]
Update Settings
Updates Determined by Expiration of a Periodic Timer
[Update Needed]
Play Note Corresponding to Current Heading Error
Every 20 msecs.
[Subject Location Update]
[No Update Needed]

Figure 3.24 MidiDisplay activity diagram.

There are several settings that are maintained within the MidiDisplay process. A low note and high note are maintained to bound a range of notes that will be used to signal the magnitude of the subject heading error. A frequency setting will specify the update interval, which is specified in milliseconds. Finally, the standard midi-defined channel and program numbers are maintained to specify a particular instrument.

The *subject positioning update* is processed as follows. The heading error is calculated by determining the absolute value of the acute angle defined by the difference between the subject's current bearing to destination and the subject's current heading (see Figure 3.25). The error value is then normalized and scaled to fall between the lowest and highest notes as currently defined within the MidiDisplay process. The value is presented such that an error of 180 degrees is rendered as the lowest note; an error of zero degrees is rendered as the highest note. An error of 90 degrees would appear as the note number occurring half way through the range, a 60 degrees error occurring two-thirds of the way through the range, and so on. The update is performed on a periodic basis, so *subject positioning update* events that arrive before the configured time threshold are not rendered.

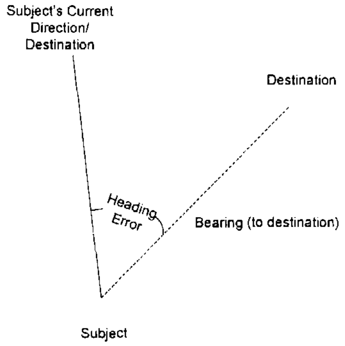


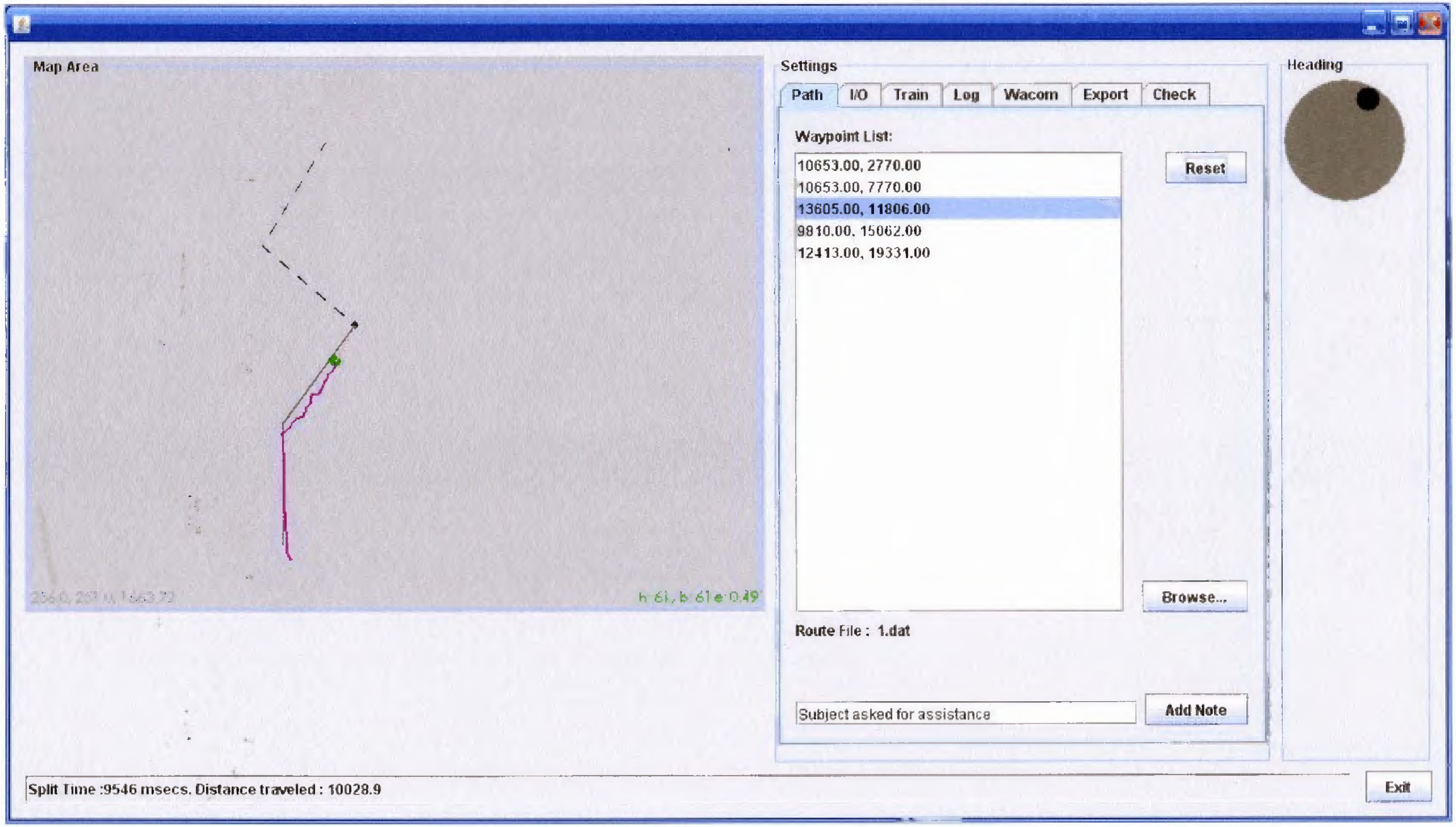
Figure 3.25 Heading error.

An additional setting is provided for the MidiDisplay sub-process. If the investigator specifies Silence Mode in the 'feedback parameters settings' action, the MidiDisplay will behave slightly differently. Note selection will be determined as previously presented, however, an on-target condition will manifest differently. If the subject is on-target, defined by a heading error of less that three degrees, the highest notes are suppressed and a silent condition will be presented.

3.10.2.1.6 Graphical Display Sub-Process. This display is used for two purposes: (1) as a monitor for the investigator during experiments and (2) as an aid while developing and debugging.

As shown in the Services Startup activity diagram, the GraphicalDisplay process is always started. It schedules itself to run on a periodic interval. This interval is determined by the Java Abstract Windowing Toolkit (AWT) system, and is outside the control of the evaluation system. Since the scheduling only effects the frequency of updates to the graphical view of the system, this level if indeterminateness does not present a problem for data collection and reporting of user performance.

The GraphicalDisplay contains a graphic canvas area that appears on the investigator's screen. This canvas area represents the current navigation route, the current destination, and the subject's current position. Figure 3.26 shows the investor's screen with the darker grey graphic canvas area labeled "MapArea."


Map Area
h 61, b 61 e 0.49
Settings
Path
I/O
Train
Log
Wacom
Export
Check
Heading
Reset
Browse...
Add Note
Exit

Waypoint List:

10653.00, 2770.00
10653.00, 7770.00
13605.00, 11806.00
9810.00, 15062.00
12413.00, 19331.00

Route File : 1.dat

Subject asked for assistance

Split Time :9546 msecs. Distance traveled : 10028.9

Figure 3.26 Investigator's screen showing investigator controls and "Map Area" navigational status.

The navigation route is shown by a combination of solid and dashed grey lines. Solid lines represent segments of the route that precede the current waypoint; dashed segments represent the uncompleted portion. The user's location is shown as a colored circle, which appears as red, yellow or green depending on the magnitude of their heading error. The current waypoint destination is represented with a black dot. The magenta colored line shows the path that the subject has followed while attempting the current navigation.

This sub-process responds to three events. These are represented by the initial guard conditions shown in the activity diagram in Figure 3.27. A *subject position update* results in a relocation of the colored circle representing the navigator's current position. The color is updated based on the prevailing heading error. A *waypoint arrival* event is treated by indexing the current destination to the next destination: the black dot is moved to the next destination and the segment fonts are updated accordingly. Finally, the third event, a route reset, is handled by indexing the back dot back to the route origin and undoing any progress represented with the solid grey lines.

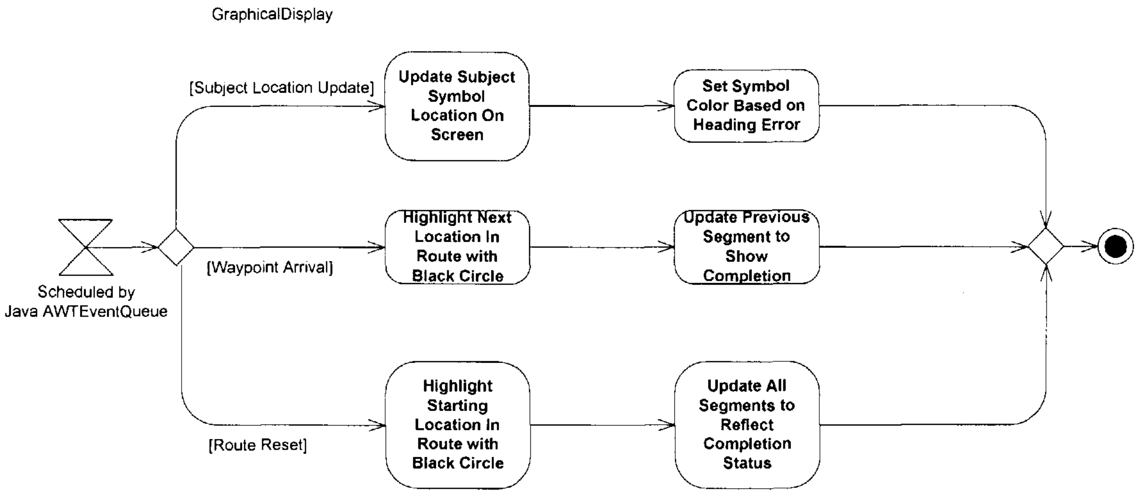

GraphicalDisplay
[Subject Location Update]
Update Subject Symbol Location On Screen
Set Symbol Color Based on Heading Error
Highlight Next Location In Route with Black Circle
Update Previous Segment to Show Completion
[Waypoint Arrival]
Scheduled by Java AWTEventQueue
Highlight Starting Location In Route with Black Circle
Update All Segments to Reflect Completion Status
[Route Reset]

Figure 3.27 GraphicalDisplay activity diagram.

3.10.2.1.7 Data Sampler Sub-Process. The final sub-process considered here is the DataSampler. Like the other sub-processes, the data sampler schedules itself to run periodically. It runs itself each 200 milliseconds after the completion of the previous sampling event. Like the TabletProcessor, AnnouncerDisplay and the GraphicalDisplay, the DataSampler runs unconditionally under all experiment conditions.

The DataSampler begins with a simple decision. These are described with the guard conditions shown in Figure 3.28. If an experiment trial is not in progress, this sub-process simply goes back to sleep. Conversely, when the subject is actively navigating between the start point and the route end point, the process will capture the subject's prevailing position, waypoint and heading error. These are stored for subsequent processing.

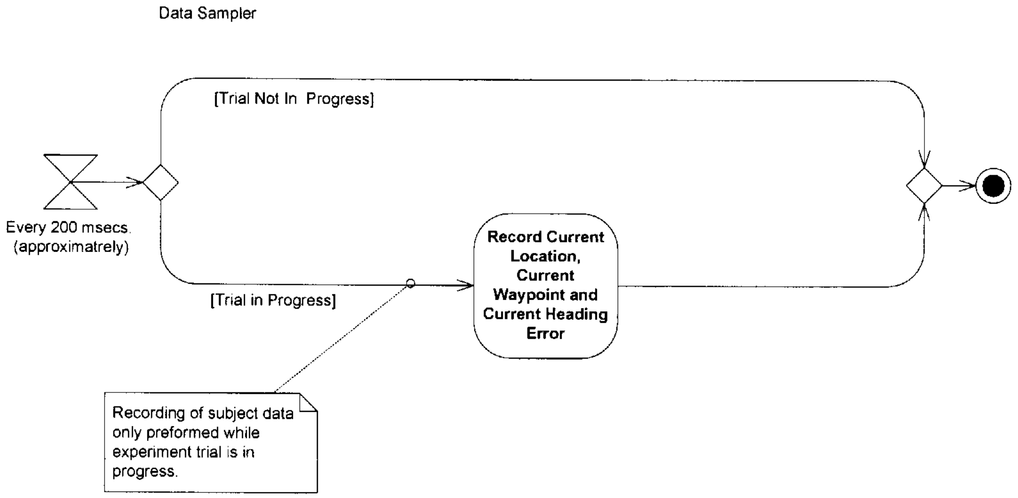

Data Sampler
[Trial Not In Progress]
Every 200 msecs. (approximatrely)
[Trial in Progress]
Record Current Location, Current Waypoint and Current Heading Error
Recording of subject data only preformed while experiment trial is in progress.

Figure 3.28 Data Sampler activity diagram.

3.10.3 Development View

When building complex systems, it is difficult to jump from requirements directly to an implementation. Following Kruchten 4+1 model, the Use Cases View and Process View have been offered to begin this narrowing process. With these views established, it follows that the Development View (Figure 3.29) can be described next.

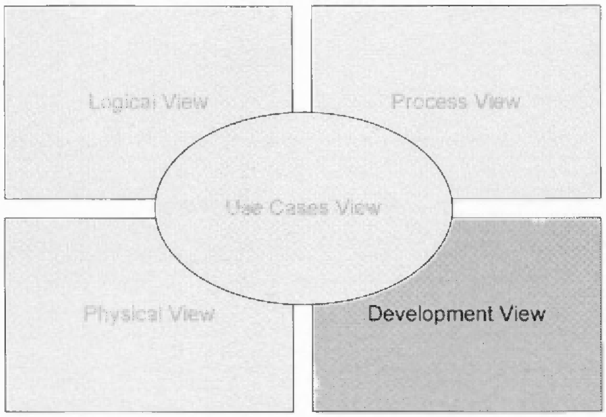


Figure 3.29 Kruchten's 4+1 model - development view.

The Development View describes how a system's parts are organized and is helpful in organizing the many layers of functionality within the system architecture. (Miles & Hamilton, 2006). With the requirements enumerated, and the high level functional parts identified (the GIS, location sensing system, user interface, and botGuide); it follows that the components can be identified to deliver the required functionality. This section will provide several items that complete the Development View.

Initially, an overview of the system software will be provided. Next, a subsystem to component decomposition is provided to identify the major software components comprising each subsystem. A component diagram, a primary artifact used within UML, is provided to illustrate the decomposition.

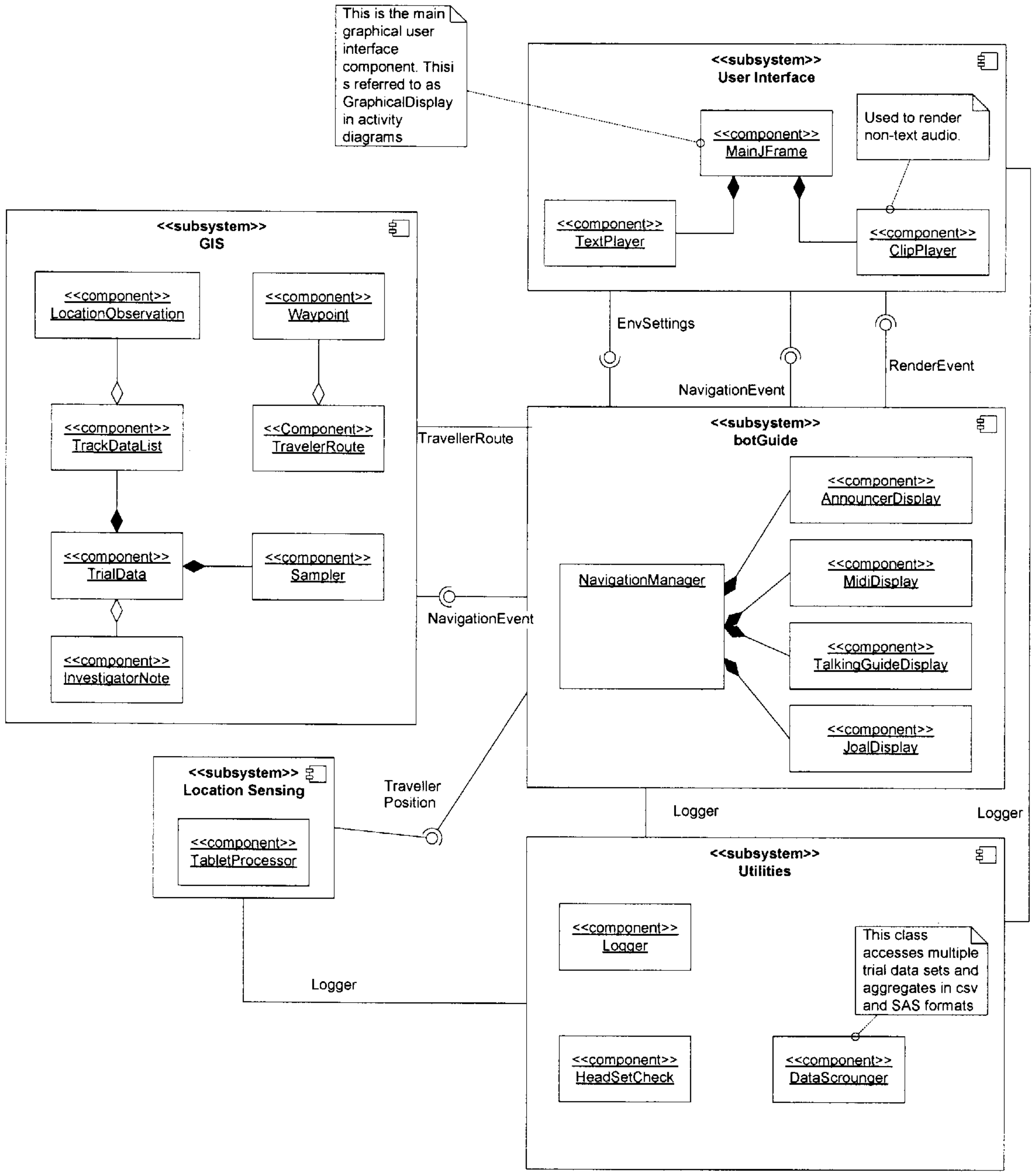
Finally, several details are discussed that would aid a new developer to this project (i.e., the *developer's* view). These details include external dependencies, source code management, logging of system status, and reporting of trial results.

Subsequently, in the Logical View, further refinement will be shown which identifies greater detail about the system's component design.

3.10.3.1.1 Software Description. Several factors influenced the decision for a programming environment and execution platform for the evaluation system. In the preceding Process View section, multiple processing tasks were described that provide the necessary capabilities of the system. Due to the need to perform these operations in parallel, a parallel or multi-threaded operating environment is dictated. Additionally, considering the desire for future adaptability (requirement G.4), a modern is object oriented programming environment is strongly suggested. Finally, considering the requirement for platform independence (requirement G.3), Java has been selected as the programming environment and the execution platform for the system (Note, the Java system is a programming language AND an execution platform).

Within the domain of object oriented programming, much work has been done to study and improve the engineering process. One such area is the application of Design Patterns (Gamma, Helm, Johnson & Vlissides, 1995). It is not the intent to comment on or revise this work, but to identify significant influences from *patterns* that has entered this work. Following common practice, an effort has been made to apply good design patterns wherever possible. Similarly, following practice, an effort has been made to avoid the use of common antipatterns (Brown, Malveau and Mowbray, 2001). One common pattern is used frequently throughout this work: the 'Observer/Observable' pattern. When employed, this pattern involves two acting roles: the subject and the observer. The observer registers with the subject identifying events that are of interest, the subject complies by passing messages to the observer at the occurrence of such events. Multiple observers are free to register with a subject. As with mainstream graphical applications, the taux evaluation system uses this pattern extensively for its own graphical as well as audio user interface needs.

3.10.3.1.2 Subsystem Decomposition. In order to further describe the evaluation system, a decomposition of the main subsystems is provided. Within each subsystem, several main components are employed to implement the use cases and activities described in the prior sections. In UML, component diagrams are used to identify major functional areas within a software system. The component diagram (Figure 3.30) shows the primary subsystems of the evaluation system and the major components that are developed to implement them. A new category is also added named Utilities, this captures components that fall outside of the main subsystems described thus far. The major subsystems are identified in the figure (Figure 3.30); these are enclosed in the 5 largest boxes. Within each subsystem's box, the major components used within that subsystem are identified. These components will be described in further detail subsequently, in the Logical View section.


This is the main graphical user interface component. Thisi s referred to as GraphicalDisplay in activity diagrams

Used to render non-text audio.

This class accesses multiple trial data sets and aggregates in csv and SAS formats

<<subsystem>>
User Interface
<<component>>
MainJFrame
<<component>>
TextPlayer
<<component>>
ClipPlayer
<<subsystem>>
GIS
<<component>>
LocationObservation
<<component>>
Waypoint
<<component>>
TrackDataList
<<Component>>
TravelerRoute
<<component>>
TrialData
<<component>>
Sampler
<<component>>
InvestigatorNote
EnvSettings
NavigationEvent
RenderEvent
TravellerRoute
NavigationEvent
<<subsystem>>
botGuide
<<component>>
AnnouncerDisplay
NavigationManager
<<component>>
MidiDisplay
<<component>>
TalkingGuideDisplay
<<component>>
JoalDisplay
<<subsystem>>
Location Sensing
<<component>>
TabletProcessor
Traveller Position
Logger
Logger
Logger
<<subsystem>>
Utilities
<<component>>
Logger
<<component>>
HeadSetCheck
<<component>>
DataScrounger

Figure 3.30 Component diagram.

For readers not familiar with UML, several notations found in the component diagram require a brief explanation. Components are shown as boxes and use UML's stereotype notation, with a label of <<component>> or <<subsystem>> at the top. A glyph representing a tabbed frame appears at the upper right hand corner. Rectangular boxes without this glyph are simply objects. Lines between components represent relationships. Additional decorations can further describe the relationship. An open diamond is an aggregation, where multiple occurrences of the distant object may appear in the closer object. A solid diamond describes a composition, commonly referred to in object-oriented terminology as a "has-a" relationship. In the component diagram (Figure 3.30), NavigationManager has several composition components: TalkingGuideDisplay, MidiDisplay, AnnouncerDisplay and JOALDisplay. Lastly, the ball and socket connectors represent interfaces. Interfaces are high level specifications allowing flexibility and independence between the associated components. In the evaluation system, interfaces are established between the subsystems to easily permit future adaptation.

3.10.3.2 System Software Component Details. The following software components were used to assemble and build the evaluation system as described in this work. These are documented here, in detail, for the purposes of reproducibility:

Table 3.3 Software Components and Revision Levels

Component	Software download reference	Version
Operating System – Windows XP	CDROM	Version 2002 Service Pack 2
Java	http://java.sun.com	1.6.0-beta2-b86
Wacom Driver	http://www.wacom.com/productsupport/drivers.cfm?os=XP&product=XD	4.96-8
Wacom Library for Java	http://www.csl.sony.co.jp/person/rekimoto/java/jwintab/	1.0
Cepstral Text-to-Speech Synthesis	http://www.cepstral.com/downloads/	4.1.4
FreeTTS	http://freetts.sourceforge.net/docs/index.php	1.2
Java3D	http://java.sun.com/products/java-media/3D/downloads/index.html	1.5.0
OpenAL Cross Platform 3D audio	http://www.openal.org/	1.9.3.0
Java Bindings for OpenAL / Sound3D (JOAL)	https://joal.dev.java.net/	1.1b03
Integrated Development Environment - netbeans	http://www.netbeans.org	5.5 Release Candidate 1
Integrated Development Environment – Microsoft Visual Studio	http://ist.njit.edu/software/download.php	2005

3.10.3.3 Coordinate Systems. Several of the subsystems within the evaluation system use their own coordinate systems to represent spatial data. The libraries used to access these subsystems are fixed, leaving no opportunity to manipulate the coordinate systems used. An approach was needed to allow transformation between the coordinate systems of interest. Also, the requirement for future adaptability (requirement G.4) dictates that additional interfaces should be readily accommodated. In practice, an investigator should be able to add a new location sensing system or a new audio display and have these seamlessly integrate with the existing system. Coding ease and performance characteristics of the overall system were considered in developing a solution to manage the coordinate system data. A strategy to maintain one global coordinate system and an arbitrary number of local coordinate systems was adopted; this approach is described within this section.

Within the evaluation system, five different coordinate systems are used. The attributes of these systems are mixed: most are two dimensional while one is three, some use integers for their coordinates while other use real values, and not all of the systems are 'right handed'. Given the variation, an approach is adopted to maintain a global coordinate system and map into and out of local systems on an as-need basis. For the current implementation, the global coordinate system is coincident with the tablet coordinate system. This mapping was performed simply for convenience; this mapping can be easily decoupled in the future as new location sensing systems are integrated. The following table (Table 3.4) summarizes the coordinates systems managed by the evaluation system:

Table 3.4 Coordinate Systems and Their Attributes

System	Dimension Units	Number of Dimensions	Right Handed
Global	Real	2	Yes
Tablet	Integer	2	Yes
Screen	Integer	2	No
3D Audio (JOAL)	Real	3	Yes
GIS	Real	2	Yes

In order to simplify programming within the evaluation system, a small set of conventions are adopted. All GIS data is always transformed to and maintained in the global coordinate system. As a result, any class that supplies data to GIS components must first transform them to the global coordinate system. The supplying class must maintain its own transformation from its local coordinate system to the global coordinate system. The contract between the objects is slightly different when the data flows in the other direction. A class that is interested in accessing the global data stored within the GIS component is responsible for maintaining its own global-to-local transformation. However, the called GIS class performs the actual transformation. By performing the transformation at the provider end, the necessary code is reduced and the burden of coding the transformations is significantly decreased. An example should help clarify the contract.

The following code fragments, from the object named 'Waypoint' (source file Waypoint.java) illustrates the interface for callers. Waypoint.java is a GIS object.

```
public class Waypoint {
    //
    // note: unnecessary source code omitted for readability
    //
    Point2D.Double pD; // the point

    public Waypoint(int x, int y) {
        //
        // the constructor expects the x,y values to already be
        // transformed to global coordinates
        //
        pD = new Point2D.Double(x, y);
    }

    public Point2D getPoint2D(AffineTransform at) {
        //
        // the caller will provide their own transformation (at) that
        // transforms from global -> local coordinates
        // pdPrime is instantiated to hold the transformed coordinate pair
        // pdPrime is returned to the caller
        //
        Point2D.Double pDPrime = new Point2D.Double();
        pDPrime = (Point2D.Double)at.transform(pD, pDPrime);
        return pDPrime;
    }

    public Point2D.Double getPoint2D() {
        //
        // simply return the point, in global coordinates
        //
        return pD;
    }
}
```

Several observations should be made. Any caller using the Waypoint(x,y) constructor must transform their coordinates to the global coordinate system before calling the constructor. A companion example, from the caller's perspective, follows below. Subsequently, any object interested in examining the coordinates of the Waypoint object will take one of two paths. They will either call getPoint2D() without a transformation parameter and get the untransformed (global) coordinates, or, they will call getPoint2D(transform) supplying their own transformation object and getting the point of interest returned within their local coordinate system. To summarize, any GIS object will store coordinate data in the global coordinate system and provide coordinates in global coordinates or in a localized system when a transformation has been offered.

The next code example illustrates a caller performing a transformation before providing it to a GIS component. In this fragment, the TabletProcessor object transforms its data to the global coordinate system and calls the NavigationManager GIS component:

```
public class TabletProcessor extends Thread {
    //
    // note: unnecessary source code omitted for readability
    //

    private NavigationManager navMgr;
    private double scaleFactor = 1.0d;
    private AffineTransform t2gTransform;

    public TabletProcessor(NavigationManager navMgr) {
        this.navMgr = navMgr;
        //
        // t2gTransform is tablet to global coordinate system transformation
        //
        t2gTransform = new AffineTransform(scaleFactor, 0.0d, 0.0d, scaleFactor, 0.0d,
0.0d);
        //
        // we never transform from global into the local tablet coordinate system,
        // sot the inverse transformation is not constructed
        //
    }

    public void run() {
        // note looping logic and timer logic omitted for readability
        // arg[] array is the structure returned from jwintab wacom library call
        // source is omitted for readability
        //
        Point2D.Double p = new Point2D.Double((double)arg[0], (double)arg[1]);

        // t2gTransform.transform(p,p) performs local->global transform before calling
        // setSubjectLocationAndTwistAngle() method
        //
        // note the following call transforms point p using t2gtransform before sending
        //
        navMgr.setSubjectLocationAndTwistAngle(
                                    (Point2D.Double)t2gTransform.transform(p,p),
                                     angle );
    }
}
```

When accessing data from a GIS component, callers are most likely to be interested in the data represented within their own local coordinate system. In the following example, JoalDisplay passes its global->local transformation object (j2gTransform) to the Waypoint object:

```
public class JoalDisplay extends Thread implements Observer {

    private double scale = 100.0d;
    private AffineTransform j2gTransform;
    private AffineTransform g2jTransform;

    private Point2D psource;

    public JoalDisplay()  {
        // joal -> global transformation
        j2gTransform = new AffineTransform(scale, 0.0d, 0.0d, scale, 0.0d, 0.0d);
        // global -> joal transfomation
        g2jTransform = j2gTransform.createInverse();
        }
    }

    public void run() {

        while (!stop) {
            // note looping logic and timer logic omitted for readability
            //
```

```
              ...
              // source of the sound is at the waypoint
              // pass the global->local transformation to the Waypoint object, point in
              // local coordinate system will be displayed
              psource = ((navMgr.getTRoute().getCurrentWaypoint().getPoint2D(g2jTransform);

             // process sounds through JOAL with new coordinates
             ....
         }
     }
}
```

After this code executes, the values in psource will be relative to JOALDisplay's local coordinate system.

By introducing and maintaining a global coordinate system, it is easy to localize transformation definitions completely within interested components. The code line count was kept small and testing has shown that system performance is acceptable. By passing the locally managed transformation object to the GIS components, transformations can be centrally calculated without intimate knowledge of a specific caller's environment. This approach provides the ability to transform from any arbitrary coordinate system to a global coordinate system, and provides a system that is easily extended to include new sensing infrastructure or new audio displays.

3.10.3.4 Source Code Control. A current practice for software development teams is to use a configuration management system to manage and track the development and evolution of a software system. Such systems offer several valuable advantages: systems can be easily restored to known/good states, what-if scenarios can be explored and easily accepted or rejected, release and test procedures can be indexed to a discreet system state, managers can identify milestones points (also known as tags and branches), and changes can be easily shared and coordinated amongst team members.

Not all these benefits accrue to the evaluation system, but, using a source code configuration management approach provides a significant benefit. Since the state of the system is an independent variable, different instantiations could results in different experiment outcomes. With a configuration management system, the system software state can be controlled.

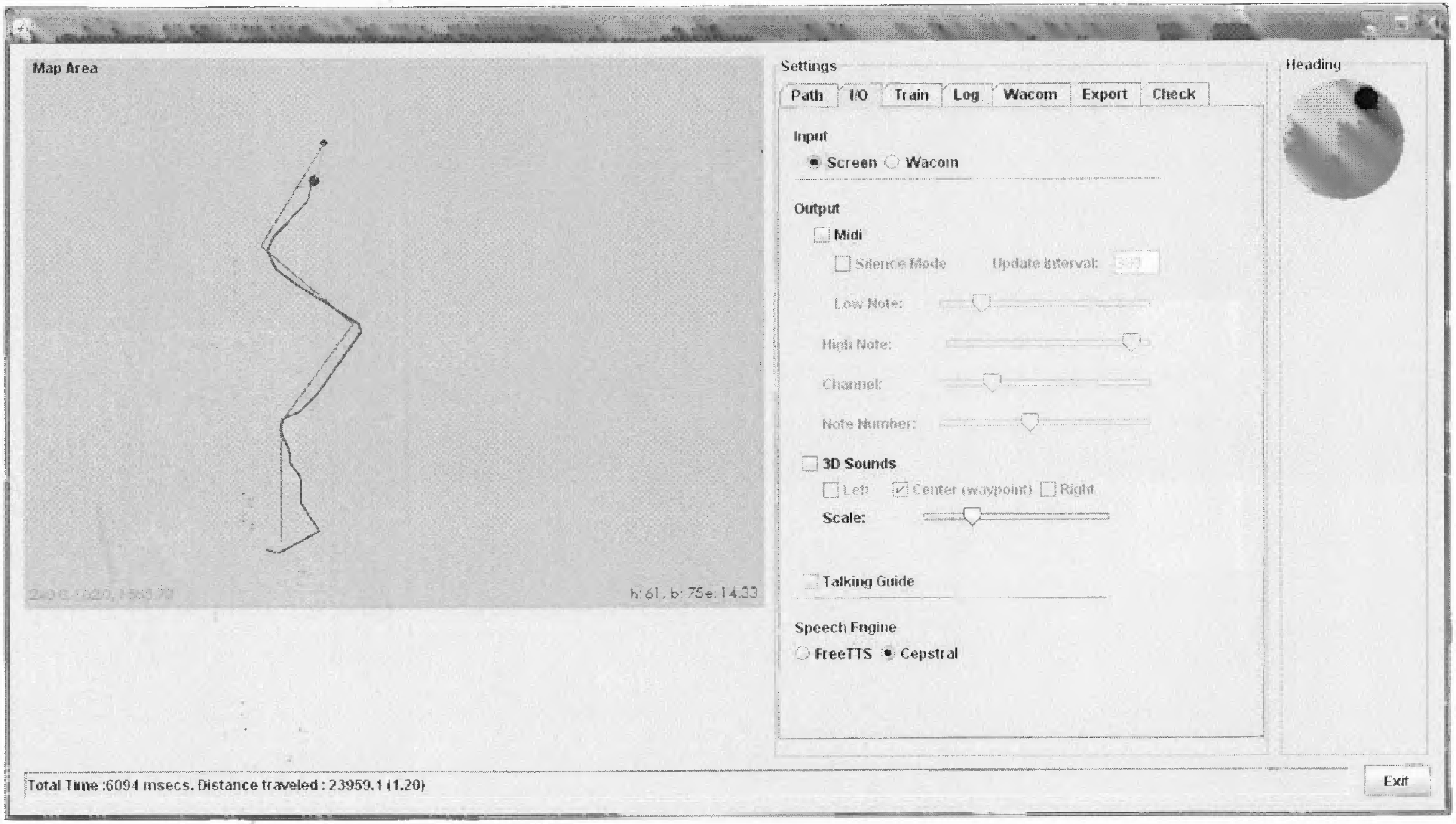
The evaluation system software is kept under the control of a configuration management system named *subversion*. The software for this configuration management system is available for download via an open source arrangement from http://subversion.tigris.org/. There are several other dependencies that need to be established to use subversion; these are detailed in the installation instructions at the project site. The version used for this work is 1.4.2. Additionally, TortoiseSVN (revision 1.4.0, Build 7501 - 32 Bit) and the subversion plugin for netbeans (revision 1.1.20.42.1.1) are used to integrate to the subversion repository.

The subversion repository created and maintained for this project resides at http://sur50r.homeip.net/njit-repos-taux. Access to the repository can be obtained by written request to lutz@acm.org.

Subversion manages the entire project as a collection of files. Following a 'vault' metaphor, a user can check out, modify, and check in project contents. At each atomic operation against the repository (check in, copy, delete, move), a serial revision number is incremented and recorded. To satisfy previously stated advantage of controlling the independent variable of software state, the subversion revision level is recorded with all experiment trial data for reference.

3.10.3.5 Testing. System testing is performed on a frequent basis. Currently, the tests are not performed in an automated fashion. After each bug fix or enhancement, specific tests are performed to confirm the recent change. Additionally, a series of regression tests are performed to confirm that the system continues to perform as it did prior to the update.

For convenience to the developer, the system can be operated for testing either from the Wacom tablet or exclusively from the graphical interface. By selecting the Screen option within the I/O tab on the tool, a tester can navigate with the mouse on the on the graphic canvas area. Audio feedback will be rendered properly. Since there is no way to simulate Wacom puck rotation with the mouse, the tester can drag the knob at the right to adjust the direction of navigation (Figure 3.31).


Map Area
h:61, b:75e:14.33
Settings
Path
I/O
Train
Log
Wacom
Export
Check
Heading
Exit

Input

● Screen ○ Wacom

Output

☐ Midi

☐ Silence Mode Update Interval:

Low Note:

High Note:

Channel:

Note Number:

☐ 3D Sounds

☐ Left ☑ Center (waypoint) ☐ Right

Scale:

☐ Talking Guide

Speech Engine

○ FreeTTS ● Cepstral

```
Total Time :6094 msecs. Distance traveled : 23959.1 (1.20)
```

Figure 3.31 Testing: navigating from the screen.

3.10.3.6 System Logging and Reporting. Several output modes are possible with the evaluation system. For development related activities, such as debugging and testing, system logging is performed. For research data collection, the capability is provided to export data into common formats. These two output methods are described below.

3.10.3.6.1 System Logging. Following industry standard practice, the application code contains calls to report informational and diagnostic events at important process points. Settings are available to tailor the level and destination of reporting on a conditional basis. The current implementation is built completely within the evaluation system; however, this was done with the foresight that a more fully-featured open source offering could be easily substituted. The source code is instrumented in each class with a simple object reference:

```
private logger = UILogger.getLogger();
```

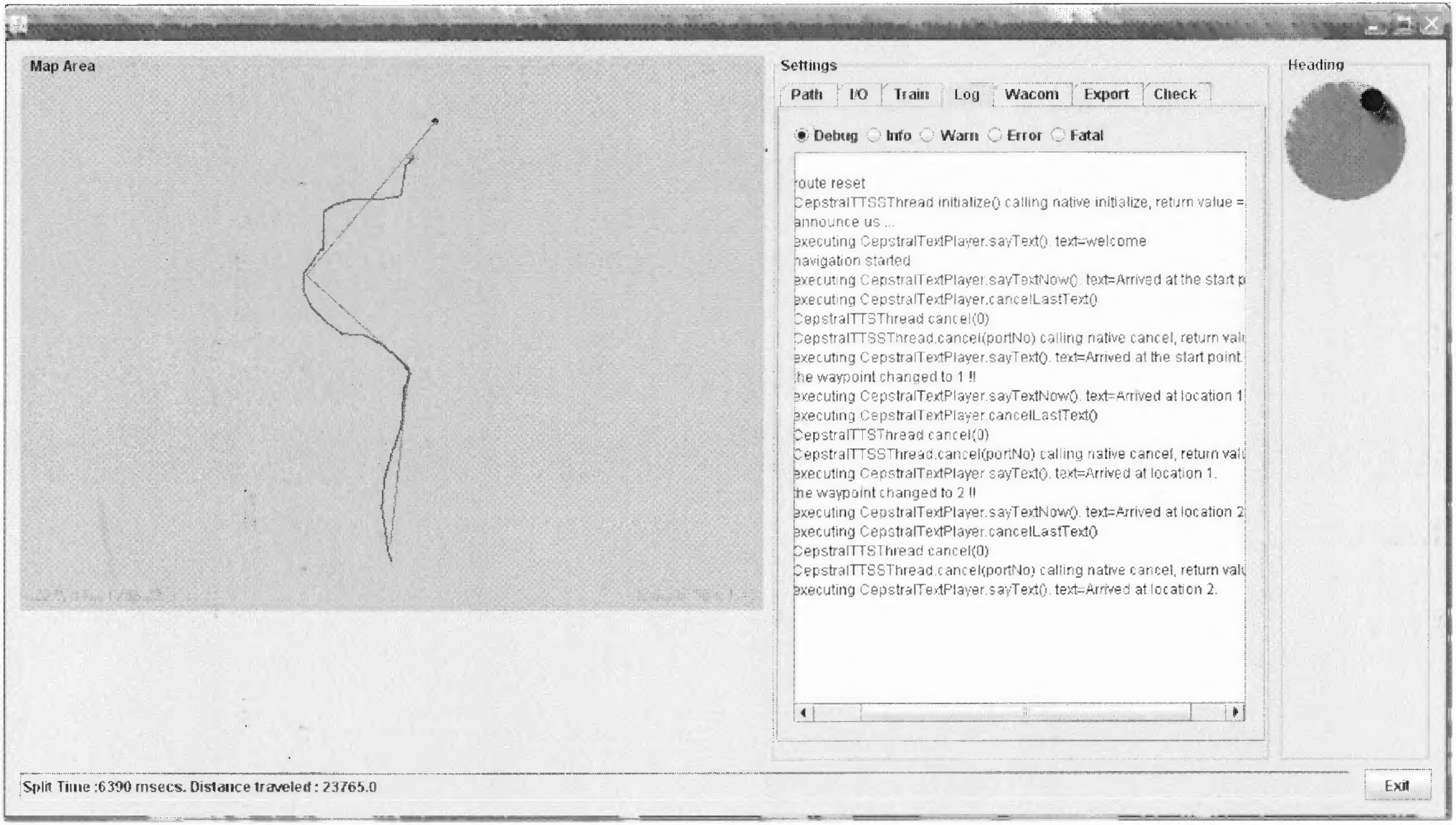
Once this object is in place, the developer places diagnostic statements within their code:

```
logger.info("unable to register point");
```

or

```
logger.debug("changing state to " + navState);
```

From the user interface, while testing or running experiments, the investigator can examine the logged information and elect different levels of detail. Figure 3.32 illustrates what the investigator sees on the investigator's console. A tab under the settings panel is used to set levels and view the log. A set of radio buttons correspond directly to the log levels identified by the developer in the log.*level*() calls: Debug, Info, Warn, Error, Fatal. A selection on the left of the scale (Debug) provides the most detail; a selection on the right side (Fatal) provides the least amount of detail. Logged messages are displayed in the text field that follows. Messages contain the time of the message, the calling calls and the text of the message.



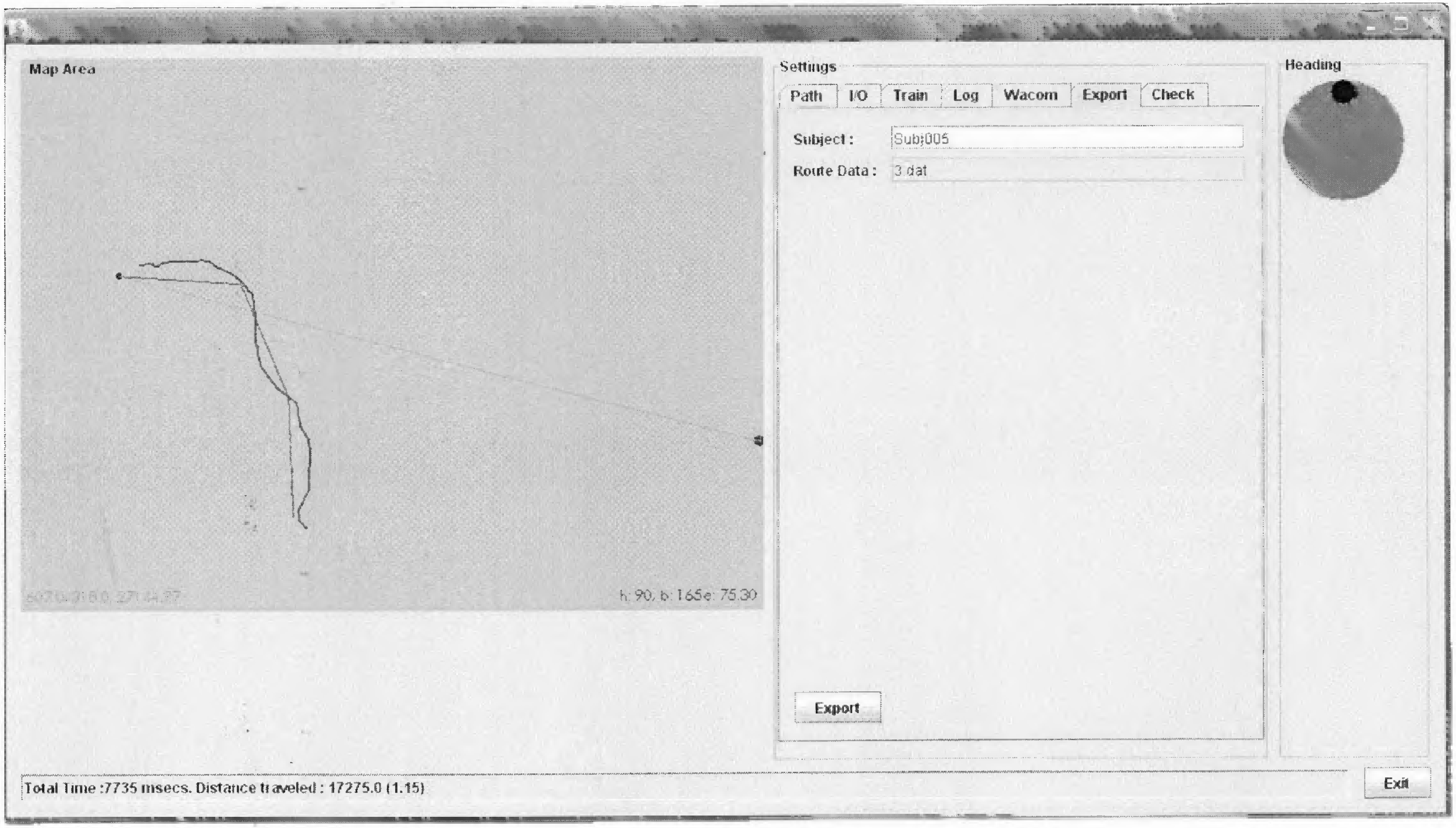
● Debug ○ Info ○ Warn ○ Error ○ Fatal

```
route reset
CepstralTTSThread initialize() calling native initialize, return value =
announce us ...
executing CepstralTextPlayer.sayText(). text=welcome
navigation started
executing CepstralTextPlayer.sayTextNow(). text=Arrived at the start p
executing CepstralTextPlayer.cancelLastText()
CepstralTTSThread cancel(0)
CepstralTTSThread.cancel(portNo) calling native cancel, return val
executing CepstralTextPlayer.sayText(). text=Arrived at the start point
the waypoint changed to 1 !!
executing CepstralTextPlayer.sayTextNow(). text=Arrived at location 1
executing CepstralTextPlayer.cancelLastText()
CepstralTTSThread cancel(0)
CepstralTTSThread.cancel(portNo) calling native cancel, return val
executing CepstralTextPlayer.sayText(). text=Arrived at location 1.
the waypoint changed to 2 !!
executing CepstralTextPlayer.sayTextNow(). text=Arrived at location 2
executing CepstralTextPlayer.cancelLastText()
CepstralTTSThread cancel(0)
CepstralTTSThread.cancel(portNo) calling native cancel, return val
executing CepstralTextPlayer.sayText(). text=Arrived at location 2.
```

Split Time :6390 msecs. Distance traveled : 23765.0

Figure 3.32 Logging output.

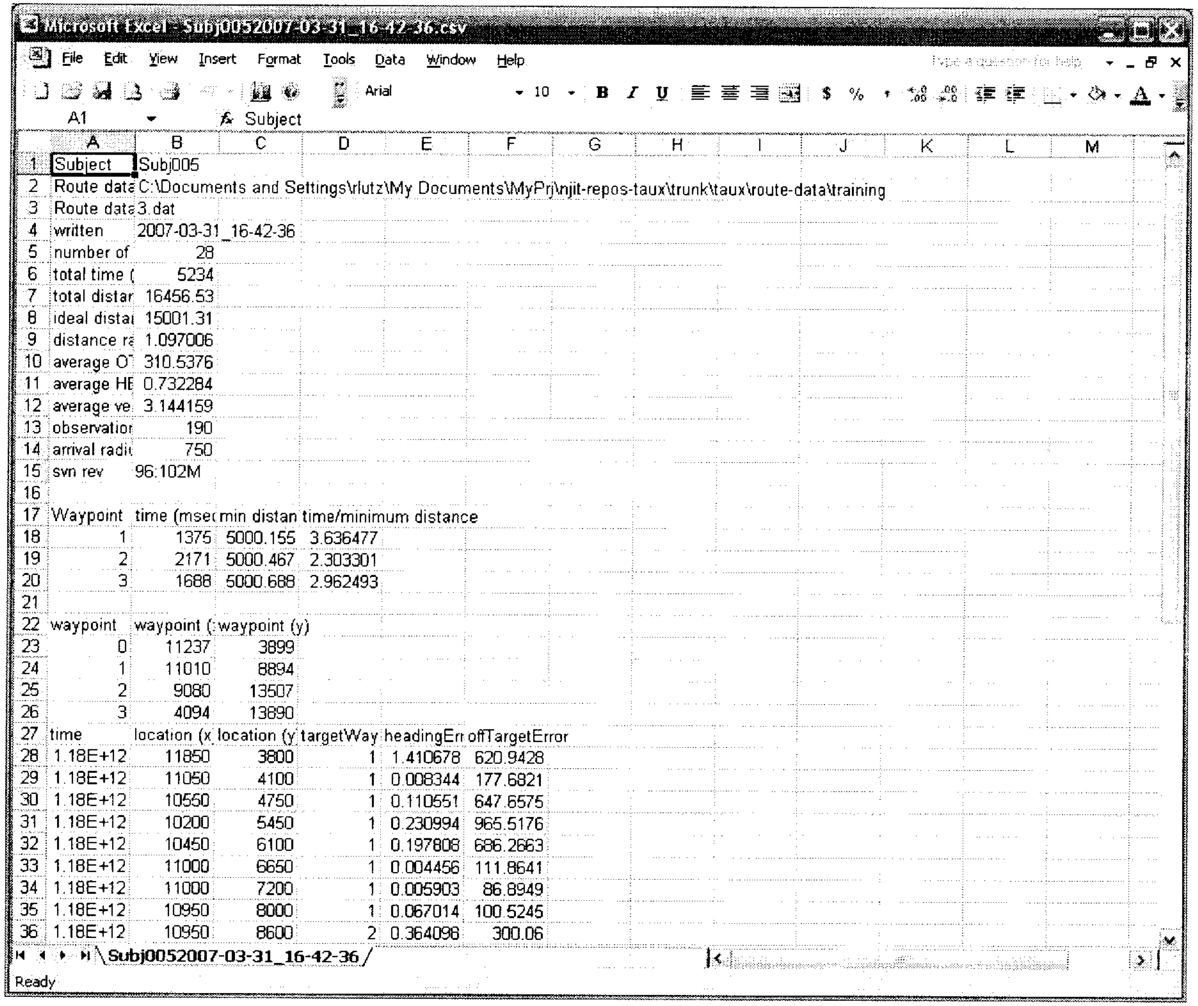
3.10.3.6.2 Reporting. Data collected in experiments is output to two formats: a comma separated text file and a data input file formatted for the R statistical analysis package. A comma separated text file can also be known as comma separated value file, or a CSV file. The CSV can be processed by a spreadsheet program or processed programmatically for subsequent inquiry. Appendix M contains an example CSV file. The CSV is generated by navigating to the Export tab in the evaluation system at the end of trial as shown in Figure 3.33. The CSV data can be viewed in a spreadsheet application as shown in Figure 3.34.


Map Area
h: 90, b: 165e: 75.30
Settings
Path
I/O
Train
Log
Wacom
Export
Check
Export
Heading
Exit

Subject : Subj005
Route Data : 3.dat

Total Time :7735 msecs. Distance traveled : 17275.0 (1.15)

Figure 3.33 Exporting data from experiment.


Microsoft Excel - Subj0052007-03-31_16-42-36.csv
File
Edit
View
Insert
Format
Tools
Data
Window
Help
Arial
10
A1
Subject
Subj0052007-03-31_16-42-36
Ready

	A	B	C	D	E	F
1	Subject	Subj005				
2	Route data	C:\Documents and Settings\rlutz\My Documents\MyPrj\njit-repos-taux\trunk\taux\route-data\training				
3	Route data	3.dat				
4	written	2007-03-31_16-42-36				
5	number of	28				
6	total time (	5234				
7	total distar	16456.53				
8	ideal distai	15001.31				
9	distance ra	1.097006				
10	average OT	310.5376				
11	average HE	0.732284				
12	average ve	3.144159				
13	observatior	190				
14	arrival radi	750				
15	svn rev	96:102M				
16						
17	Waypoint	time (msec	min distan	time/minimum distance		
18	1	1375	5000.155	3.636477		
19	2	2171	5000.467	2.303301		
20	3	1688	5000.688	2.962493		
21						
22	waypoint	waypoint (:	waypoint (y)			
23	0	11237	3899			
24	1	11010	8894			
25	2	9080	13507			
26	3	4094	13890			
27	time	location (x	location (y	targetWay	headingErr	offTargetError
28	1.18E+12	11850	3800	1	1.410678	620.9428
29	1.18E+12	11050	4100	1	0.008344	177.6821
30	1.18E+12	10550	4750	1	0.110551	647.6575
31	1.18E+12	10200	5450	1	0.230994	965.5176
32	1.18E+12	10450	6100	1	0.197808	686.2663
33	1.18E+12	11000	6650	1	0.004456	111.8641
34	1.18E+12	11000	7200	1	0.005903	86.8949
35	1.18E+12	10950	8000	1	0.067014	100.5245
36	1.18E+12	10950	8600	2	0.364098	300.06

Figure 3.34 Experiment CSV data viewed in spreadsheet program.

The R data file is created by subsequently running a collection tool named DataScrounger. DataScounger will read each trial file and aggregate items of interest into an R input file. Example R data files are included in Appendix N.

3.10.4 Logical View

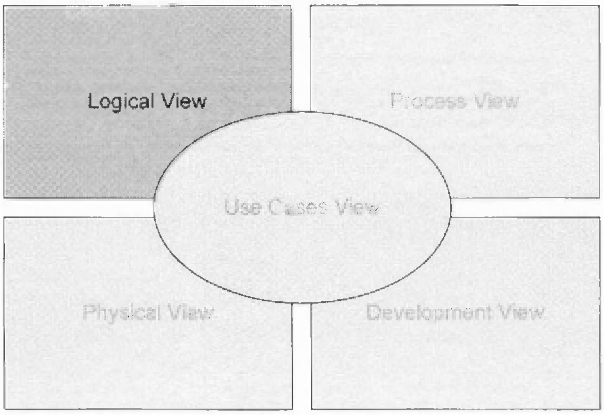


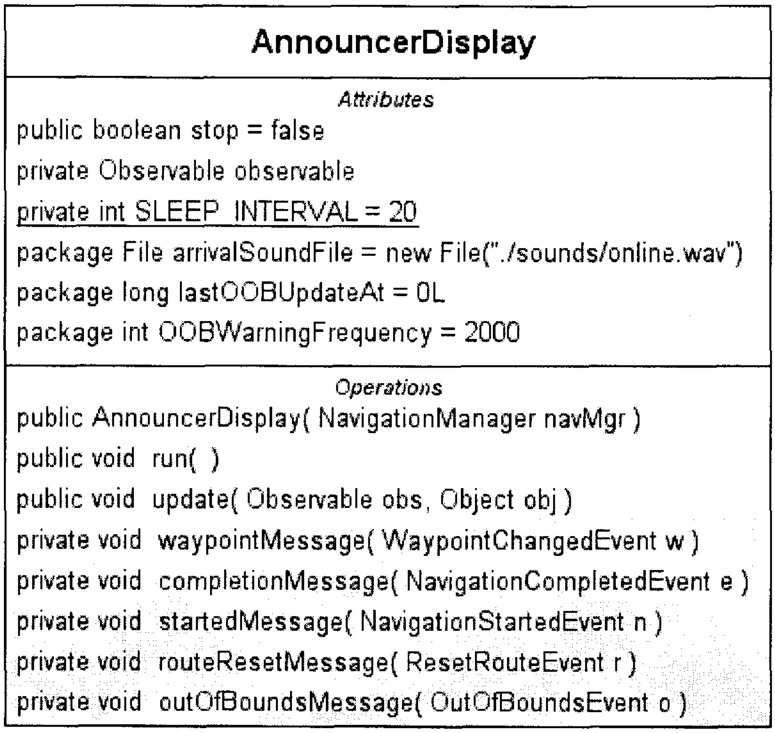
Figure 3.35 Krutchen's 4+1 model - logical view.

Referring back to Kruchten's 4+1, the Use Cases View, Process View and Development View have been described (Figure 3.35). This section will provide the Logical View, a more detailed description of the classes that make up the evaluation system. Several UML artifacts can be typically utilized within the Logical View to describe the design of a software system. Recalling Fowler's 'UML as a Sketch' approach, class diagrams will be used exclusively to describe the primary components and their fundamental attributes and operations. Details contained in timing diagrams, interaction diagrams, composite diagrams and object diagrams will be omitted here, as these details have been provided at a general level in the other artifacts and views already discussed.

This section will complete the discussion about the software components of the system. The next section, Physical View, will provide details about the physical characteristics of the system.

3.10.4.1 botGuide Subsystem. The primary component in the botGuide subsystem, and perhaps in the overall evaluation system, is the NavigationManager class. The NavigationManager is intended to be instantiated only once (this is commonly referred to as a *singleton* reference in object oriented nomenclature). Figure 3.37 contains the class diagram for NavigationManager.

As described in the previous Process View section, there are several displays that provide primary functionality for the botGuide subsystem. A typical example is AnnouncerDisplay. AnnouncerDisplay's class diagram is provided in Figure 3.36. Class diagrams for MidiDisplay, TalkingGuideDisplay, and JoalDisplay are omitted since these follow the pattern of AnnouncerDisplay closely. For information on extending the evaluation system to include completely new display types, please refer to the Advanced System Operation section.



AnnouncerDisplay

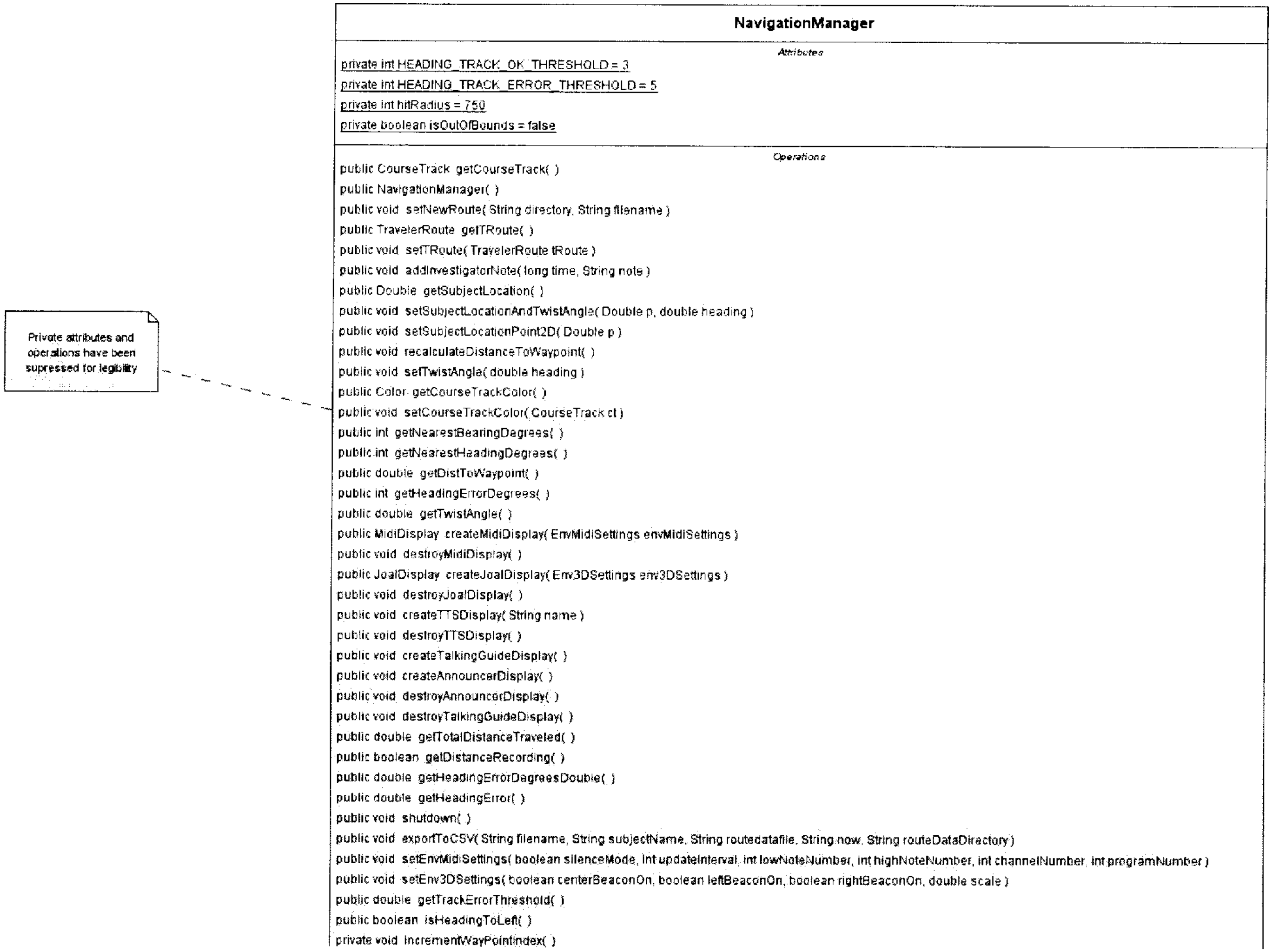
Attributes

public boolean stop = false
private Observable observable
private int SLEEP_INTERVAL = 20
package File arrivalSoundFile = new File("./sounds/online.wav")
package long lastOOBUpdateAt = 0L
package int OOBWarningFrequency = 2000

Operations

public AnnouncerDisplay(NavigationManager navMgr)
public void run( )
public void update(Observable obs, Object obj)
private void waypointMessage(WaypointChangedEvent w)
private void completionMessage(NavigationCompletedEvent e)
private void startedMessage(NavigationStartedEvent n)
private void routeResetMessage(ResetRouteEvent r)
private void outOfBoundsMessage(OutOfBoundsEvent o)

Figure 3.36 AnnouncerDisplay class diagram.

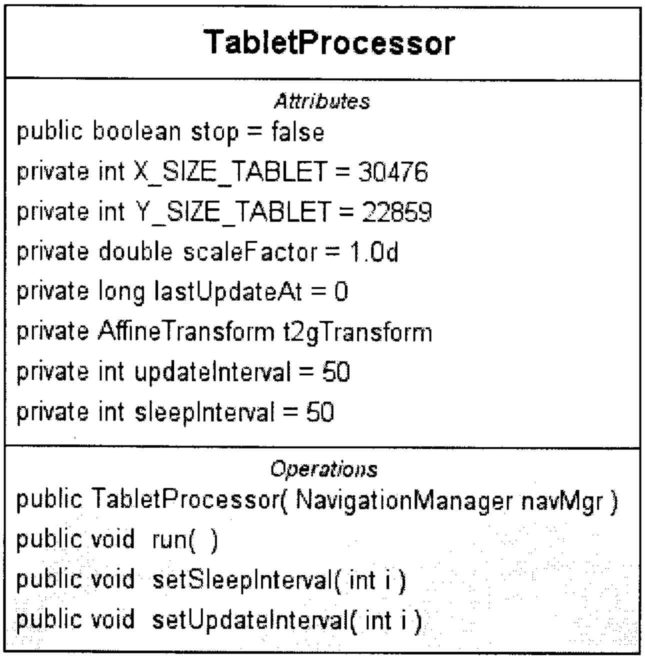

NavigationManager
Attributes
Operations
Private attributes and operations have been supressed for legibility

```
private int HEADING_TRACK_OK_THRESHOLD = 3
private int HEADING_TRACK_ERROR_THRESHOLD = 5
private int hitRadius = 750
private boolean isOutOfBounds = false
```

```
public CourseTrack  getCourseTrack( )
public NavigationManager( )
public void  setNewRoute( String directory, String filename )
public TravelerRoute  getTRoute( )
public void  setTRoute( TravelerRoute tRoute )
public void  addInvestigatorNote( long time, String note )
public Double  getSubjectLocation( )
public void  setSubjectLocationAndTwistAngle( Double p, double heading )
public void  setSubjectLocationPoint2D( Double p )
public void  recalculateDistanceToWaypoint( )
public void  setTwistAngle( double heading )
public Color  getCourseTrackColor( )
public void  setCourseTrackColor( CourseTrack ct )
public int  getNearestBearingDegrees( )
public int  getNearestHeadingDegrees( )
public double  getDistToWaypoint( )
public int  getHeadingErrorDegrees( )
public double  getTwistAngle( )
public MidiDisplay  createMidiDisplay( EnvMidiSettings envMidiSettings )
public void  destroyMidiDisplay( )
public JoalDisplay  createJoalDisplay( Env3DSettings env3DSettings )
public void  destroyJoalDisplay( )
public void  createTTSDisplay( String name )
public void  destroyTTSDisplay( )
public void  createTalkingGuideDisplay( )
public void  createAnnouncerDisplay( )
public void  destroyAnnouncerDisplay( )
public void  destroyTalkingGuideDisplay( )
public double  getTotalDistanceTraveled( )
public boolean  getDistanceRecording( )
public double  getHeadingErrorDegreesDouble( )
public double  getHeadingError( )
public void  shutdown( )
public void  exportToCSV( String filename, String subjectName, String routedatafile, String now, String routeDataDirectory )
public void  setEnvMidiSettings( boolean silenceMode, int updateInterval, int lowNoteNumber, int highNoteNumber, int channelNumber, int programNumber )
public void  setEnv3DSettings( boolean centerBeaconOn, boolean leftBeaconOn, boolean rightBeaconOn, double scale )
public double  getTrackErrorThreshold( )
public boolean  isHeadingToLeft( )
private void  incrementWayPointIndex( )
```

Figure 3.37 NavigationManager class diagram.

3.10.4.2 Location Sensing Subsystem. The location sensing subsystem currently contains one class that was created for this work. This class, TabletProcessor, has its class diagram displayed in Figure 3.38.



TabletProcessor

Attributes

public boolean stop = false
private int X_SIZE_TABLET = 30476
private int Y_SIZE_TABLET = 22859
private double scaleFactor = 1.0d
private long lastUpdateAt = 0
private AffineTransform t2gTransform
private int updateInterval = 50
private int sleepInterval = 50

Operations

public TabletProcessor(NavigationManager navMgr)
public void run( )
public void setSleepInterval(int i)
public void setUpdateInterval(int i)

Figure 3.38 TabletProcessor class diagram.

An additional class, jwintab, was utilized to interface the TabletProcessor class with the vendor supplied libraries for the wacom tablet. The class diagram for jwintab is shown in Figure 3.39.

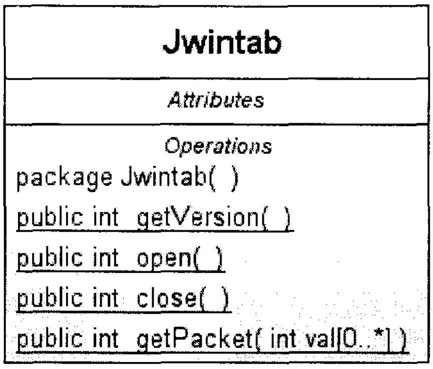

Jwintab
Attributes
Operations
package Jwintab( )
public int getVersion( )
public int open( )
public int close( )
public int getPacket(int val[0..*])

Figure 3.39 Jwintab class diagram.

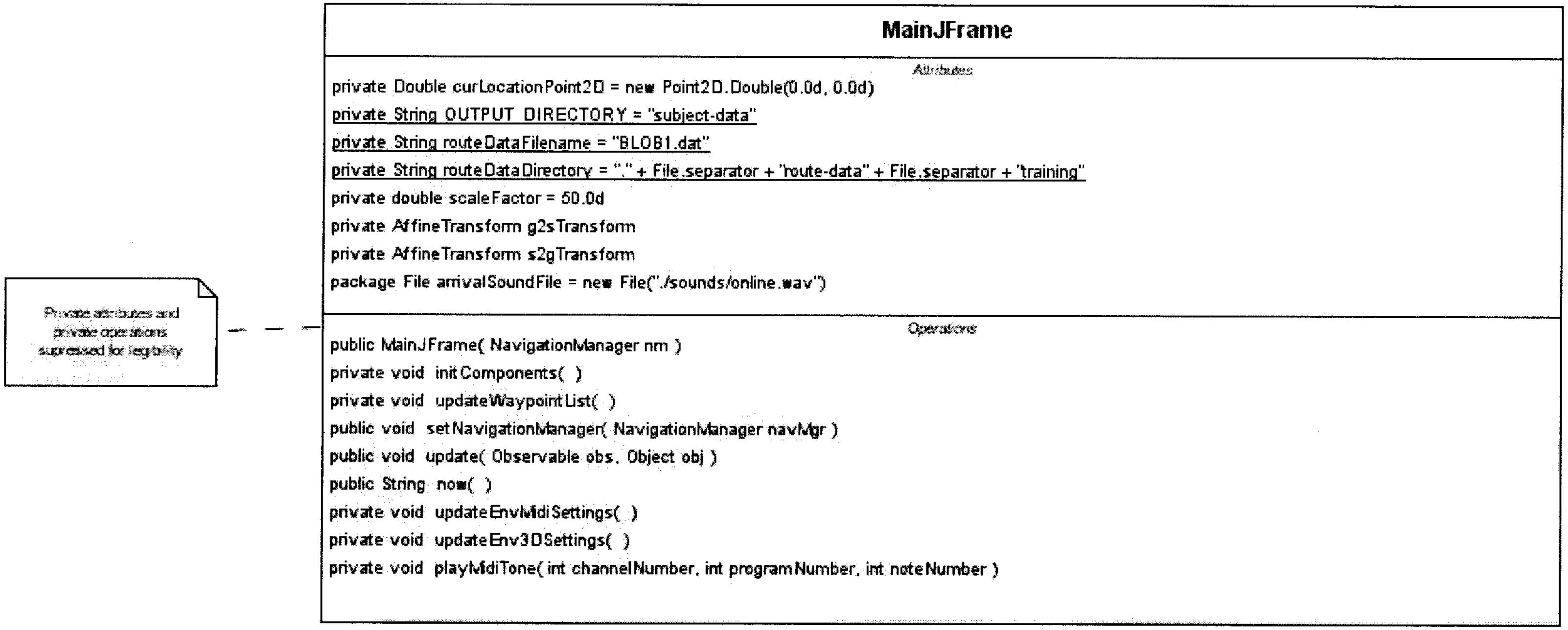

Private attributes and private operations suppressed for legibility
MainJFrame
Attributes
private Double curLocationPoint2D = new Point2D.Double(0.0d, 0.0d)
private String OUTPUT_DIRECTORY = "subject-data"
private String routeDataFilename = "BLOB1.dat"
private String routeDataDirectory = "." + File.separator + "route-data" + File.separator + "training"
private double scaleFactor = 50.0d
private AffineTransform g2sTransform
private AffineTransform s2gTransform
package File arrivalSoundFile = new File("./sounds/online.wav")
Operations
public MainJFrame(NavigationManager nm)
private void initComponents( )
private void updateWaypointList( )
public void setNavigationManager(NavigationManager navMgr)
public void update(Observable obs, Object obj)
public String now( )
private void updateEnvMidiSettings( )
private void updateEnv3DSettings( )
private void playMidiTone(int channelNumber, int programNumber, int noteNumber)

Figure 3.40 MainJFrame class diagram. Non-essential private operations and attributes are suppressed for legibility.

3.10.4.3 User Interface Subsystem. The user interface subsystems used many classes for its graphical and audio interfacing needs. The primary class, MainJFrame class, has its class diagram displayed in Figure 3.40. There are a number of classes used by the user interface subsystem for the display and manipulation of graphical components. These components: buttons, sliders, text fields, labels, forms, panels, tabs, and button groups are standard Java Swing components; their class diagrams are omitted here for this reason. For audio capability, standard components for rendering sounds notes and text-to-speech translations were utilized; class diagrams for these are omitted for the same reason.

3.10.4.4 GIS Subsystem. There are two primary sets of classes used in the GIS subsystem. The first set is used to define and maintain traveler route information. This set includes the WayPoint and TravelerRoute classes. The second set is used to collect experiment data; it contains LocationObservation, TrackDataList, TrialData and Sampler classes. The relationships between these classes were shown in Figure 3.30.

3.10.4.4.1 TravelerRoute Set. The TravelerRoute set contains two classes: TravelerRoute and Waypoint. Waypoints are the discreet turning points within a traveler's planned path. Any number of these can be assembled into an ordered list. The TravelerRoute class is used to contain such an ordered list. The TravelerRoute class also stores and exposes other route details, such as the current waypoint and distances. The Waypoint and TravelerRoute Class diagrams are found in Figure 3.41 and Figure 3.42, respectively.

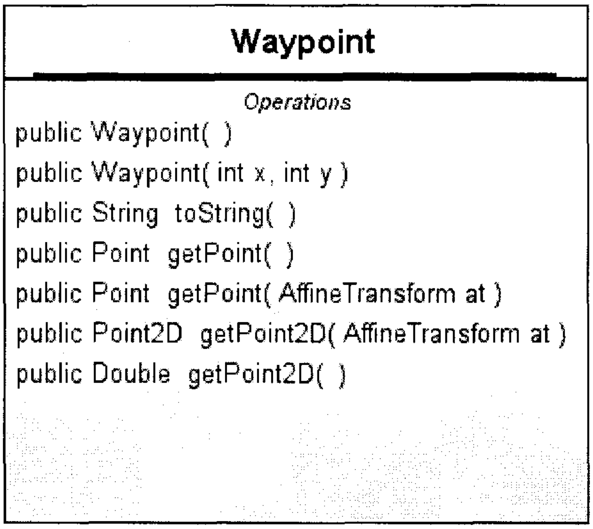

Waypoint
Operations
public Waypoint( )
public Waypoint(int x, int y)
public String toString( )
public Point getPoint( )
public Point getPoint(AffineTransform at)
public Point2D getPoint2D(AffineTransform at)
public Double getPoint2D( )

Figure 3.41 Waypoint class diagram.

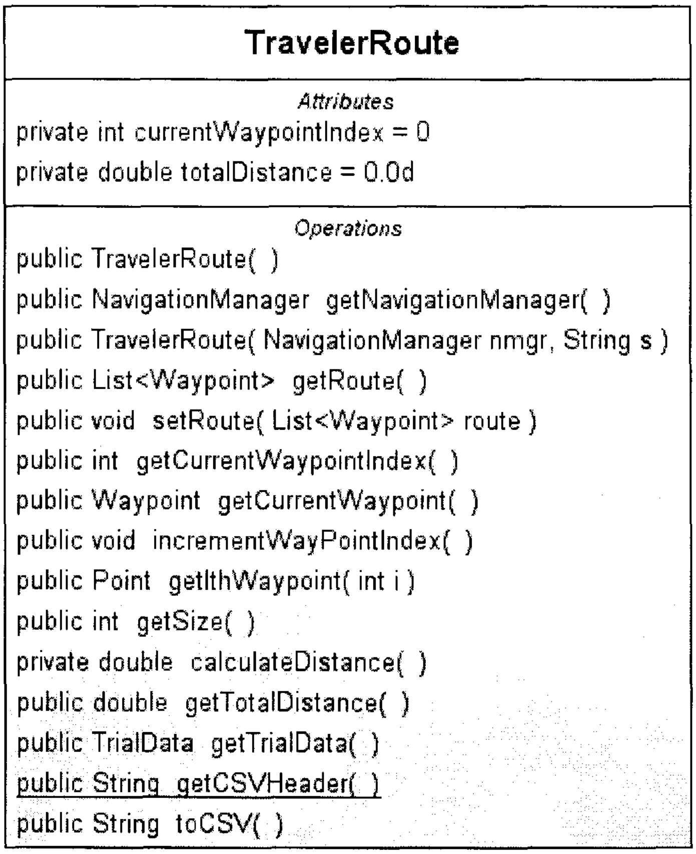

TravelerRoute
Attributes
private int currentWaypointIndex = 0
private double totalDistance = 0.0d
Operations
public TravelerRoute( )
public NavigationManager getNavigationManager( )
public TravelerRoute(NavigationManager nmgr, String s)
public List<Waypoint> getRoute( )
public void setRoute(List<Waypoint> route)
public int getCurrentWaypointIndex( )
public Waypoint getCurrentWaypoint( )
public void incrementWayPointIndex( )
public Point getIthWaypoint(int i)
public int getSize( )
private double calculateDistance( )
public double getTotalDistance( )
public TrialData getTrialData( )
public String getCSVHeader( )
public String toCSV( )

Figure 3.42 TravelerRoute class diagram

3.10.4.4.2 TrialData Set. Data collected in experiments is temporarily housed in memory objects before being exported to disk files. The classes that describe these objects are LocationObservation, TrackDataList, TrialData and Sampler. The primary object in this set is the TrialData class. Figure 3.43 contains class diagram for the TrialData class.

LocationObservation objects (Figure 3.44) are created for each observation of a subject's location as registered by the NavigationManager. The observation contains the user's location along with the heading error and time of recording. The collection of LocationObservations for a given journey (or track) are assembled in an ordered list; this list is contained in a TrackDataList. See Figure 3.45 for the class diagram for the TrackDataList.

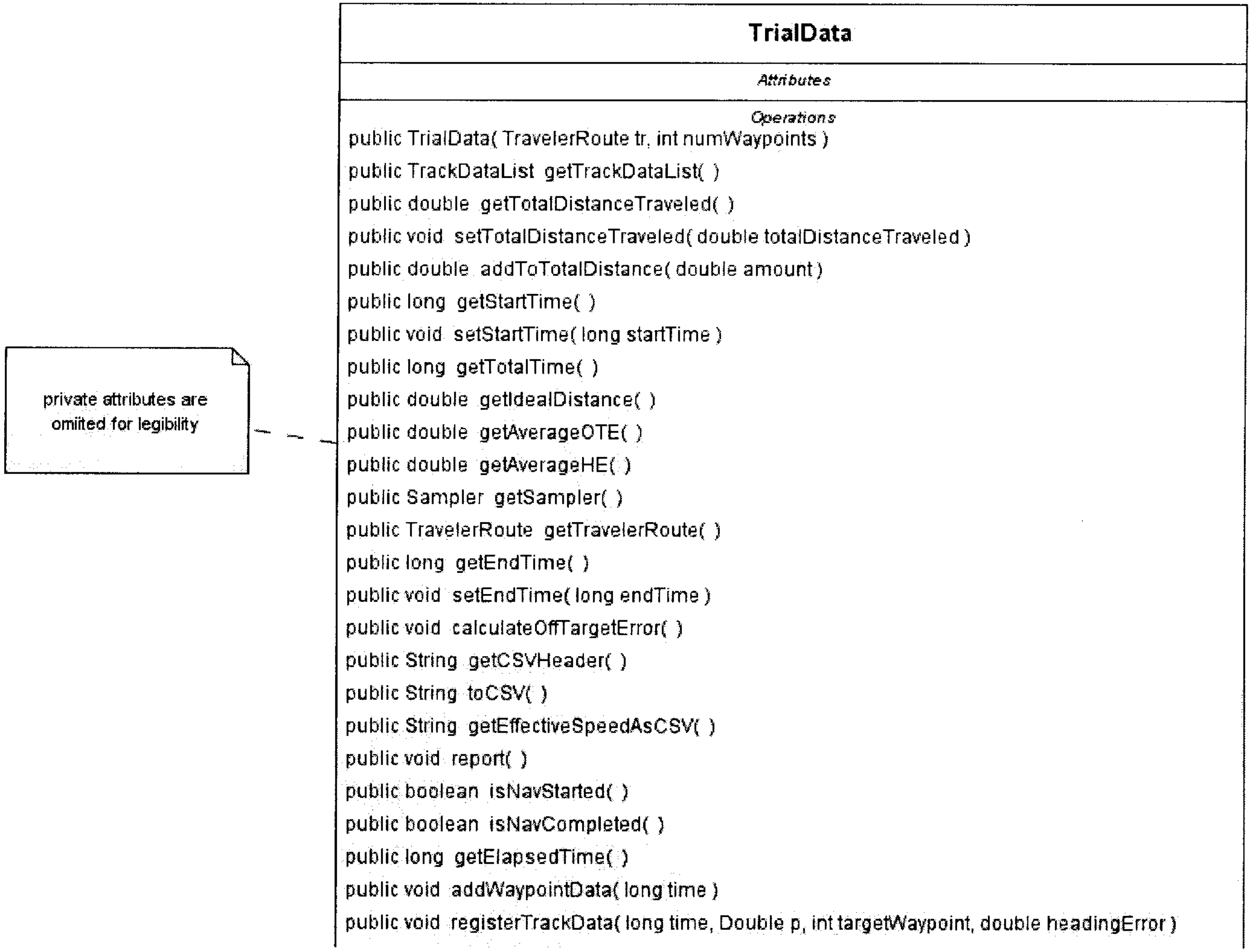
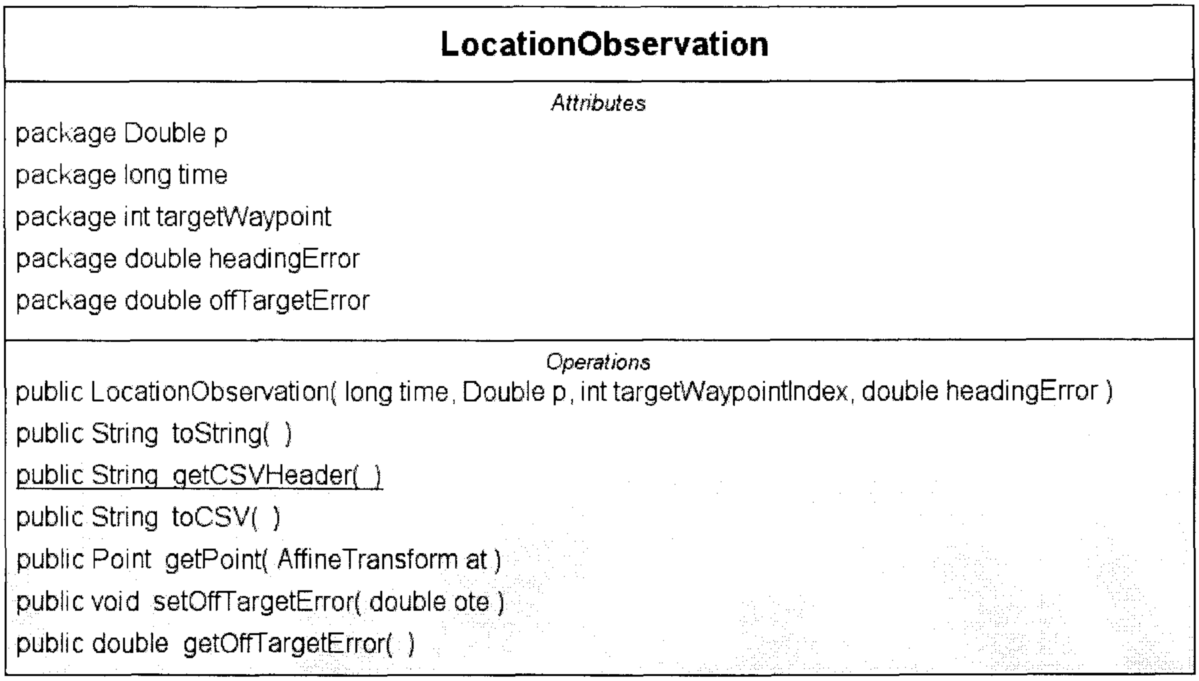

TrialData
Attributes
Operations
public TrialData(TravelerRoute tr, int numWaypoints)
public TrackDataList getTrackDataList( )
public double getTotalDistanceTraveled( )
public void setTotalDistanceTraveled(double totalDistanceTraveled)
public double addToTotalDistance(double amount)
public long getStartTime( )
public void setStartTime(long startTime)
public long getTotalTime( )
public double getIdealDistance( )
public double getAverageOTE( )
public double getAverageHE( )
public Sampler getSampler( )
public TravelerRoute getTravelerRoute( )
public long getEndTime( )
public void setEndTime(long endTime)
public void calculateOffTargetError( )
public String getCSVHeader( )
public String toCSV( )
public String getEffectiveSpeedAsCSV( )
public void report( )
public boolean isNavStarted( )
public boolean isNavCompleted( )
public long getElapsedTime( )
public void addWaypointData(long time)
public void registerTrackData(long time, Double p, int targetWaypoint, double headingError)
private attributes are omitted for legibility

Figure 3.43 TrialData class diagram.



LocationObservation

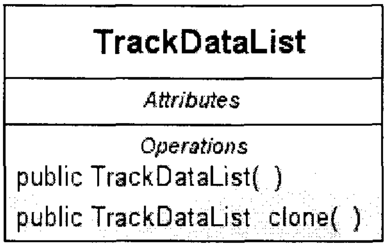
Attributes

package Double p
package long time
package int targetWaypoint
package double headingError
package double offTargetError

Operations

public LocationObservation(long time, Double p, int targetWaypointIndex, double headingError)
public String toString( )
public String getCSVHeader( )
public String toCSV( )
public Point getPoint(AffineTransform at)
public void setOffTargetError(double ote)
public double getOffTargetError( )

Figure 3.44 LocationObservation class diagram.



TrackDataList

Attributes

Operations

public TrackDataList( )
public TrackDataList clone( )

Figure 3.45 TrackDataList class diagram.

The final class in the TrialData set is the Sampler class. The sampler class runs as its own thread, and builds the TrackDataList object contained in TrialData with multiple LocationObservation objects. As described in the Process View section (Figure 3.28), the Sampler runs on a periodic interval and only collects data while a navigation task is in process. The class diagram for Sampler is seen in Figure 3.46.

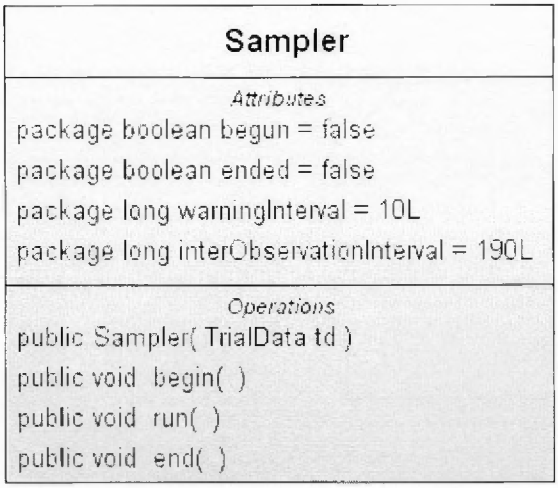

Sampler
Attributes
package boolean begun = false
package boolean ended = false
package long warningInterval = 10L
package long interObservationInterval = 190L
Operations
public Sampler(TrialData td)
public void begin( )
public void run( )
public void end( )

Figure 3.46 Sampler class diagram.

3.10.5 Physical View

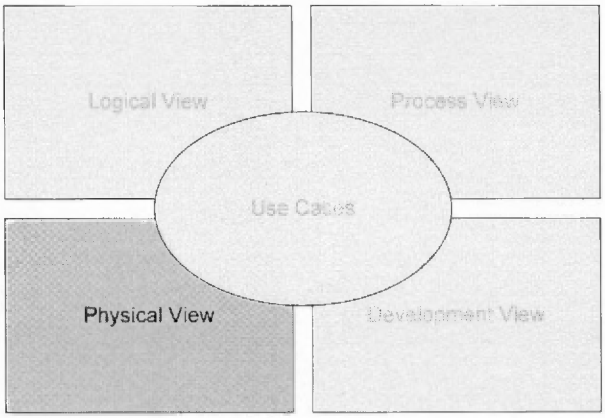

Logical View
Process View
Use Cases
Physical View
Development View

Figure 3.47 Kruchten's 4+1 physical view.

All the views with Kruchten's 4+1 how now been considered, with the exception of the Physical View. The following section will consider the physical details of the system. First, the system's hardware components are introduced. Secondly, the software components needed to run a complete evaluation system are described. Finally, instructions are provided for the independent investigator to deploy and run their own instance of the evaluation system.

3.10.5.1 System Components

For the current evaluation system, the major system components are: a desktop or laptop computer, two stereophonic headsets, a Wacom tablet device and a microphone. The components and related interface details for these components are shown in Figure 3.48. Table 3.5 contains details of the components utilized in the current evaluation system.

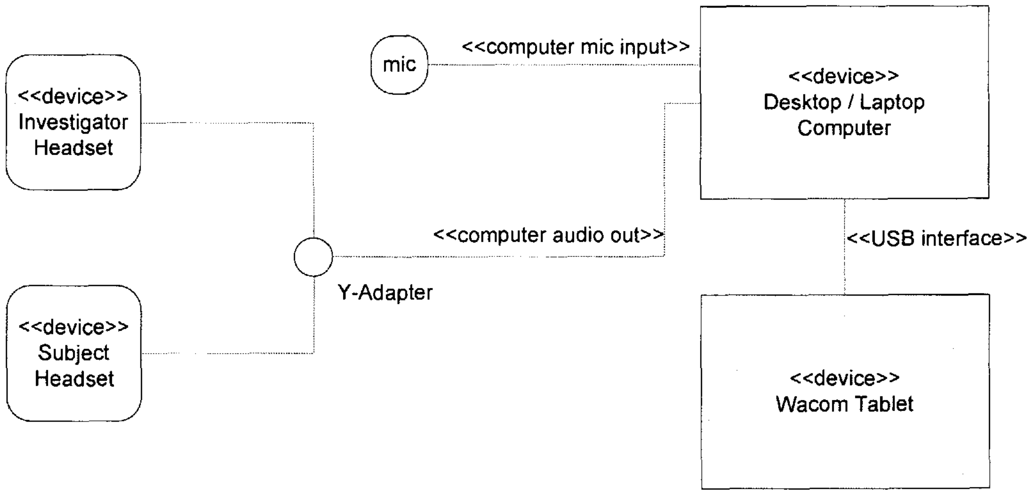


Figure 3.48 System components diagram.

Table 3.5 Description of Hardware Components

Item	Part Number	Notes
Laptop Computer	Sony VGN FE-790G laptop	Intel Centrino Duo 1.83Ghz, 2GB Main Memory
Wacom Tablet	Intuos 2 XD-0912-U tablet with 4D mouse	
Binaural Headset	Bose around-ear headphones 110V	Subject headset
Binaural Headset	Altec Lansing AHS502i	Investigator headset
1/8” Stereo Y-Adapter	Radio Shack Catalog# 42-2570	
Monaural Microphone	(part number unavailable)	Used to test headset levels

3.10.5.2 Software Components

The evaluation system requires taux.jar to execute. This archive contains the executable classes that have been developed as part of this research. Additionally, there are dependencies on several open source and vendor supplied application libraries. These are summarized in Table 3.6.

Table 3.6 Software Library Dependencies

Archive	Source	Notes
taux.jar	This research	
JNICepstralWrapper.dll	NJIT AudioBrowser Project	
jsapi.jar	FreeTTS distribution	Must accept terms and conditions of Java Speech API after installing FreeTTS library
en_us.jar	FreeTTS distribution	
cmulex.jar	FreeTTS distribution	
cmudict04.jar	FreeTTS distribution	
cmu_us_kal.jar	FreeTTS distribution	
joal.jar	JOAL Distribution	
joal.dll	JOAL Distribution	
swing-layout-1.0.jar	Netbeans distribution	
ceplang_us.dll	Cepstral Distribution	
swift.dll	Cepstral Distribution	
efsadu.dll	http://www.dll-files.com/dllindex/dll-files.shtml?efsadu	provides support for file encryption. More details at http://msdn2.microsoft.com/en-us/library/ms995356.aspx
Msjava.dll	http://www.dll-files.com/dllindex/dll-files.shtml?msjava	module that provides the COM support for Java programs to run in the Windows operating system
Jwintab.dll	http://www.sonycsl.co.jp/person/rekimoto/java/jwintab/	Requires wintab32.dll
Wintab32.dll	Wacom Distribution	Appears in c:\windows\system32 after wacom wintab software installation
OpenAL32.dll	OpenAL installer for Windows	Install from http://www.openal.org/downloads.html
wrapOal.dll	OPenAL installer for Windows	Install from http://www.openal.org/downloads.html

3.10.5.3 Deployment and Running of the Evaluation System

The following steps should be performed to install and run the evaluation system. First, two libraries need to be loaded onto the target environment. These are Wintab application software for the Wacom tablet and the OpenAL Installer. If the Cepstral voices are to be used, a copy of Cepstral's software should be loaded and licensed from http://www.cepstral.com. Alternatively, FreeTTS can be used. Next, the taux project should be downloaded from the subversion repository at svn://sur50r.homeip.net/njit-repos-taux/taux. Establishing the dependencies listed above, the evaluation system is started with the following command line:

```
java -Xms256m -Xmx256m -classpath "%CP%" -Djava.library.path="%DLLPATH%" taux.Main
```

The variables %CP% and %DLLPATH% refer to the proper paths for the libraries listed in Table 3.6.

Alternatively, invoking the script named *run.bat* from within the downloaded taux project will establish the proper paths for dependencies and start the taux application. A listing of *run.bat* is provided below. The %PROJDIR% and %SWINGJAR% variables will need to be adjusted to tailor the script to work in the deployed environment.

```
echo running taux ....

rem only the following section should need adjustment
SET PROJDIR=C:\Documents and Settings\rlutz\My Documents\MyPrj\njit-repos-
taux\trunk\taux
SET SWINGJAR=C:\Program Files\netbeans-5.5rc1\platform6\modules\ext\swing-layout-
1.0.jar

rem the rest are derived
SET DISTDIR=%PROJDIR%\dist
SET EXTDIR=%PROJDIR%\extjars
SET FREETTSDIR=%EXTDIR%\freetts1.2\lib

SET CP=%DISTDIR%\taux.jar
SET CP=%CP%;%FREETTSDIR%\jsapi.jar
SET CP=%CP%;%FREETTSDIR%\freetts.jar
SET CP=%CP%;%FREETTSDIR%\en_us.jar
SET CP=%CP%;%FREETTSDIR%\cmulex.jar
SET CP=%CP%;%FREETTSDIR%\cmudict04.jar
SET CP=%CP%;%FREETTSDIR%\cmu_us_kal.jar
SET CP=%CP%;%EXTDIR%\joal.jar
SET CP=%CP%;%SWINGJAR%

SET DLLPATH=%PROJDIR%\dlls
```

```
SET

java -Xms256m -Xmx256m ^
  -classpath "%CP%" ^
  -Djava.library.path="%DLLPATH%" taux.Main
```

3.11 Advanced System Operation and Extension

In the system requirements it was specified that the system should easily provide future adaptations. In many circumstances, when considering the body of literature available for auditory display of spatial information, it will be desirable to move beyond the standard displays provided by the current evaluation system and to add completely new displays. By following the architecture and conventions provided by the system it should be easy to define completely new mechanisms and behaviors and bind them into the system. There are several steps required to add a new display:

- Create the class(es) that implement the new behavior
- Add Display's start and stop methods to the NavigationManager class
- Add controls to the GUI (MainJFrame object) to allow for selection and configuration of the new Display object

3.11.1 Creating the New Display Class

The following ArbitraryDisplay code skeleton is provided to illustrate what functions a class should implement to create a new display. In order to complete ArbitraryDisplay, the investigator would replace the areas noted with "TODO" labeling. These labels are identified in **BOLD** type in the following code skeleton. Providing logic in these specific areas should be all that is needed to complete the implementation of a new display.

```
/* ArbitraryDisplay.java
 *
 * Created on December 28, 2008, 11:42 AM
 *
 */

package taux.arbitrary;
```

```
import edu.njit.audiobrowser.utilities.UILogger;
import java.awt.geom.Point2D;
import java.util.LinkedList;
import java.util.Observable;
import java.util.Observer;
import java.util.Queue;
import taux.navevents.NavigationCompletedEvent;
import taux.navevents.NavigationEvent;
import taux.navevents.NavigationStartedEvent;
import taux.navevents.OutOfBoundsEvent;
import taux.navevents.ResetRouteEvent;
import taux.navevents.WaypointChangedEvent;

/**
 *
 * @author gnesbitt
 */
public class ArbitraryDisplay extends Thread implements Observer {

    public volatile boolean stop = false;
    private UILogger logger = UILogger.getLogger();
    private Observable observable;
    private static final int SLEEP_INTERVAL = 20;
    private NavigationManager navMgr;
    private Queue<NavigationEvent> q;
    private Queue<Point2D> locQ;


    long lastOOBUpdateAt = 0L;
    int OOBWarningFrequency = 2000; // 2 seconds

    /** Creates a new instance of ArbitraryDisplay */
    public AnnouncerDisplay(NavigationManager navMgr) {
        this.navMgr=navMgr;
        q = new LinkedList<NavigationEvent>();
        locQ = new LinkedList<NavigationEvent>();
    }

    public void run() {
        logger.debug("arbitrary display thread started ..");

        while (!stop) {
            if (!q.isEmpty()) {
                // process the request here
                synchronized(q) {
                    Object o = ((LinkedList)q).removeLast();   // get the last item added
                    navMgr = (NavigationManager)observable;
                    if(q.size() > 0) q.clear();   // empty the queue

                    if (o instanceof WaypointChangedEvent)
                        waypointMessage((WaypointChangedEvent)o);
                    if (o instanceof NavigationStartedEvent)
                        startedMessage((NavigationStartedEvent)o);
                    if (o instanceof NavigationCompletedEvent)
                        completionMessage((NavigationCompletedEvent)o);
                    if (o instanceof ResetRouteEvent)
                        routeResetMessage((ResetRouteEvent)o);
                    if (o instanceof OutOfBoundsEvent)
                        outOfBoundsMessage((OutOfBoundsEvent)o);
                }
            }

           if (!locQ.isEmpty()) {
                synchronized(locQ) {
                    Object o = ((LinkedList)locQ).removeLast();// get the last item added
                    if(locQ.size() > 0) q.clear();             // empty the queue
                    // TODO add subject location positioning update logic here
                }
            }

            try {
                Thread.sleep(SLEEP_INTERVAL);
            } catch (Exception e) {
                e.printStackTrace();
            }
        }
        // stop logic follows
        logger.debug("ArbitraryDisplay thread stopped");
    }

    public void update(Observable obs, Object obj) {

        if ((obj instanceof NavigationEvent)) {
            synchronized(q) {
                    q.add((NavigationEvent)obj);
            }
        }
        if (obj instanceof Point2D.Double) {
            // add to the queue
            synchronized(locQ) {
                locQ.add((Point2D)obj);
            }
        }
    }

    private void waypointMessage(WaypointChangedEvent w) {
        logger.debug("the waypoint changed to " + w.getIndex() +  " !!");
        // TODO provide implementation
        }
    }

    private void completionMessage(NavigationCompletedEvent e) {
        logger.debug("navigation completed");
        // TODO provide implementation
    }

    private void startedMessage(NavigationStartedEvent n) {
        logger.debug("navigation started");
        // TODO provide implementation
    }

    private void routeResetMessage(ResetRouteEvent r) {
        logger.debug("route reset");
        // TODO provide implementation
    }

    private void outOfBoundsMessage(OutOfBoundsEvent o) {
        logger.debug("out of bounds");
        // TODO provide implementation
    }
}
```

3.11.2 Adding the Process Start/Stop Methods

The next step to integrate the new display into the evaluation framework is to incorporate the appropriate process methods for starting and stopping the ArbitraryDisplay from the NavigationManager object. First, an import statement needs to be added near the top of NavigationManager to reference the new ArbitraryDisplay object:

```
import taux.arbitrary.ArbitraryDisplay;
```

Next, the following code fragment is inserted into the NavigationManager code body. This illustrates the methods necessary to incorporate starting and stopping

ArbitraryDisplay.

```
private ArbitraryDisplay arbitraryDisplay;

public ArbitraryDisplay createArbitraryDisplay() {
    arbitraryDisplay = new ArbitraryDisplay();
    arbitraryDisplay.start();
    this.addObserver(arbitraryDisplay);
    return arbitraryDisplay;
}

public void destroyArbitraryDisplay() {
    this.deleteObserver(arbitraryDisplay);
    arbitraryDisplay.stop = true;
    arbitraryDisplay = null;
}
```

It is also possible to provide initial settings for configurable parameters for ArbitraryDisplay. Once initialized these parameters could be adjusted by NavigationManager. Additional "getter/setter" (mutator) methods would need to be added to NavigationManger to accomplish this. These mutator methods would further be exposed through the user interface to permit run time adjustment by the investigator. Additional modifications would be made to the MainJFrame class to provide this level of interaction with the ArbitraryDisplay object. These details are omitted here, but can be easily determined by following the examples of JoalDisplay or MidiDisplay in the current system.

3.11.3 Adding the Start / Stop / Configure Controls

This step follows common conventions for GUI programming within a Java application. Examination of the existing MainJFrame class should provide appropriate examples for inclusion of the new displays start/stop/configure controls. Again, the JoalDisplay and MidiDisplay references within MainJFrame class provide good examples to follow for guidance on customizing a new Display item for use from the experimental system's user interface.

This section has summarized the steps required for an investigator to extend the evaluation system to add a new display type. The next section will introduce the research questions to be considered.

CHAPTER 4

INVESTIGATING THE VIABILITY OF taux

4.1 Introduction

Chapter 3 described the architecture and interface design of taux showing how audio variations could be programmed to be connected to various portions of a user's navigation task. The instantiation of the proposed software system into a working tool answers a key research question of the thesis, that is, whether such an audio prototyping system for navigation can be built. However, two key questions remain to be addressed. First, does the transformation of the navigation task to one of path navigation on an electronic tablet effectively simulate the intended navigation task and second, can this audio prototyping system be an effective tool in evaluating possible audio designs for navigating feedback.

The thesis can evaluate the first of these questions by creating a path to be navigated and then asking participants to navigate the path. Successful navigation, that is, reaching the destination in some time that is less than deemed unacceptable is one indication that the tablet simulates a real navigation task. In addition, following the path within acceptable levels of deviation is another indication that the system models real navigation. However, neither of these evaluations tests the question directly as to whether it represents "real" navigation. There are some issues that cannot be tested until the same audio is applied to a true walking / navigation task. For example, the proprioceptive feedback is different when walking a path than when moving a puck over a path. In addition, multiple environmental cues are available in the real world, e.g., the sun on one's back, ambient sounds carrying from various directions, the wind, traffic noise etc. In addition, it is not known how the audio guidance provided will fare in a much noisier environment with many masking sounds and additional important sounds that the visually impaired person must attend to, e.g. screeching tires, etc. Given the difficulties with generalizing from the tablet environment to the real world, the question will be constrained to ask if subjects can perform navigational tasks within the confines of the scaled space. Also, because of the expense and difficulty of creating a real navigation environment, that aspect which the very purpose of this thesis is circumventing, participants will be solicited to navigate the virtual path and their performance assessed as a partial answer to this first question. Establishing validity with real world navigation will be deferred to future research.

This trial of participants will be part of a study to answer the second question, that is, whether the tool developed can be an effective prototyping tool. This second question is answered by conducting an experiment which will test a variety of audio feedbacks added to virtual navigation tasks. One of these feedbacks has been used by other researchers who have added it to real audio feedback navigation systems and the rest are reflective variations of these feedbacks that were based on complaints from both sighted and visually impaired individuals who test drove the system.

The purpose of this experiment is not to test a theory or a set of theories about how audio feedback can be best applied to navigation guidance but rather to demonstrate that taux readily supports the generation of such experiments for researchers investigating how audio can best be applied to navigation tasks. Thus, although the hypotheses that accompany this experiment represent valid hypotheses that are derived from experience gained in working with the audio feedback systems for the visually impaired, any significant findings are not directly relevant to this thesis but rather relevant to demonstrating that taux can be used effectively for the purpose building a theoretical basis on how to use sound for navigation feedback. As such the experiment described in the rest of this chapter will partially answer the first research question, if subjects will navigate using sound in the experiment at acceptable levels and fully answers the second research question if a reasonable experiment can be constructed and run using taux.

The next section of this chapter provides the approach for fully answering the question of whether a reasonable experiment can be constructed and run.

4.2 Constructing the Experiment

Several research questions were described previously. The first is addressed through a successful instantiation of the proposed system. The second question, considering the transformation of navigational tasks to the system's scaled space and representative tasks, is addressed qualitatively by an analysis of subjects' performance and a comparison of the performance to unacceptable (or random) performance. This will be addressed further in the *Results* and *Discussion* chapters. The third question considers the taux' ability to prototype varied feedbacks that are of interest to a researcher, and is the central focus of the experiment to be run.

To explore this third question, several feedback methods are carefully selected and implemented. The first, a control condition, models existing navigation systems' behavior by projecting audio messages from target locations in 3D space. Next, a derivative feedback method is constructed which augments the control case by improving it based on feedback from early system walkthroughs by both sighted and visually impaired users. A research question can be formed to compare these two conditions:

- Question 1: Can carefully constructed hints provide a better navigation experience than spatial audio alone?

Note, all of the research questions will be summarized in Table 4.1.

It is also useful to compare performance with sound alone to navigation performance which uses visual feedback. Such a comparison then serves as a baseline for what could be done with navigation if someone could see. The next condition is therefore one which provides spatial audio but also allows a user to look at the computer screen and compare their path to the one they are supposed to be taking. In addition, the same spatial audio cues are provided so as the make the condition comparable to condition 1. It is anticipated that this condition will provide the best navigation performance. Therefore this research question is postulated as:

- Question 2: Will subjects perform better if they have access to visual feedback information in addition to sound?

Two new audio display mechanisms are also introduced for comparison to the spatial audio method. The first display provides audio feedback that varies proportionally with the subject's prevailing directional error. The second display adjusts this method, by substituting silence for the sound so that the user hears nothing when he or she is on-course or nearly on-course but hears the audio feedback for error correction when off course. The question comparing these two newly added audio feedback methods is stated as follows:

- Question 3: Can the absence of audio feedback be used to communicate the relative location of a destination?

It is anticipated that subjects will perform better with the addition of the silence cue, in part, because of success with earlier pilot navigations with this type of cue.

The research questions are now summarized in Table 4.1.

Table 4.1 Research Questions

Q#	*Description* *(Note: Condition labels A0, A1, A2, B1 and B2 are further defined in the next section. These labels are provided in the following descriptions for cross-referencing purposes, as a convenience to the reader.)*
Q1	Can carefully constructed hints provide a better navigation experience than spatial audio alone? (This compares conditions A1 and A2)
Q2	Will subjects perform better if they have access to visual feedback information in addition to sound? (This compares A0 with either A1 or A2)
Q3	Can the absence of audio feedback be used to communicate the relative location of a destination? (This compares conditions B1 and B2).

Next, based on the questions that have been identified, and referencing the dependent measures (which are described subsequently), hypotheses are constructed to support the questions being asked. These are summarized in Table 4.2.

Table 4.2 Research Hypotheses

H#	*Description*
Q1.	Can carefully constructed hints provide a better navigation experience than spatial audio alone? (This compares conditions A1 and A2).
H1a.	Subjects will have a lower completion time when navigating with A2 v. A1.
H1b.	Subjects will have a better (lower) distance efficiency with A2 v. A1.
H1c.	Subjects will have a lower average veer (off target error, OTE) with A2 v. A1.
H1d.	Subjects will have a lower average angular veer (heading error, HE) with A2 v. A1.
H1e.	Subjects will prefer Talking Guide (Spatialized Audio with hints, A2) to Spatialized Audio (A1).
Q2.	Will subjects perform better if they have access to visual feedback information in addition to sound? (This compares A0 with either A1 or A2). H2a through H2d consider the comparison of A0 versus A1:
H2a.	Subjects will have a lower completion time when navigating with A0 v. A1.
H2b.	Subjects will have a better (lower) distance efficiency with A0 v. A1.
H2c.	Subjects will have a lower average veer (off target error, OTE) with A0 v. A1.
H2d.	Subjects will have a lower average angular veer (heading error, HE) with A0 v. A1.
Q2.	Continued. H2e through H2h consider the comparison of A0 versus A2:
H2e.	Subjects will have a lower completion time when navigating with A0 v. A2.
H2f.	Subjects will have a better (lower) distance efficiency with A0 v. A2.
H2g.	Subjects will have a lower average veer (off target error, OTE) with A0 v. A2.
H2h.	Subjects will have a lower average angular veer (heading error, HE) with A0 v. A2.
Q3.	Can the absence of audio feedback be used to improve communication of the relative location of a destination? (This compares conditions B1 and B2).
H3a.	Subjects will have a lower completion time when navigating with B2 v. B1.
H3b.	Subjects will have a better distance efficiency with B2 v. B1.
H3c.	Subjects will have a lower average veer (off target error, OTE) with B2 v. B1.
H3d.	Subjects will have a lower average angular veer (heading error, HE) with B2 v. B1.
H3e.	Subjects will prefer Pitch w/Silence (B2) to Varying Pitch (B1).

The next section of this chapter presents the structure of this experiment that compares five display methods that were generated using taux. As noted above, these methods are labeled as A0, A1, A2, B1 and B2, and correspond with the labels provided in the preceding tables.

4.3 Auditory Displays for Evaluation

Five display methods have been developed for the experiment. Two of these display methods are based on a spatial audio method used in prior navigation systems, i.e., conditions A1 and A2. B1 introduces a new method which varies pitch tones based on directional error; B2 offers a variation built upon B1 substituting silence for special cases. A0 is a special case; it employs a hybrid display that combines both audio and visual feedback for the purpose of establishing control data. The paragraphs which follow describe each of these feedback methods in more detail.

4.3.1 Spatialized Audio (A1)

This condition is modeled after existing wayfinding systems. A subject's destination is identified by a spoken voice, which appears to originate from that location on the tablet. The voice repeats itself at a short interval of 1 second. The sound is received as if the individual were standing on the navigation path in the location of the puck on the virtual path on the tablet. The direction of the sound will appear to come from the direction that the subject is to navigate towards. However, if the puck is not pointed toward the destination, the subject will hear the sound as if he or she is standing on the puck's location and facing a direction that is away from the target in the same direction as the puck is pointed. For example, if the destination's location is on or toward the left of the puck on the tablet, the sound will be heard predominately in the left ear. Conversely, a target location on the right of the puck will be dominant in the right ear. As a subject changes direction to point toward a destination, the sound will appear centered, in front of the subject, and become equally balanced between the left and right ear. Unfortunately, similar feedback is provided when the puck is pointing directly opposite to the desired location, as humans lack the ability to discriminate between sounds coming from their front from back. (Unfortunately, humans cannot, unlike cats, move their ears to resolve this directional problem.)

4.3.2 Spatialized Audio with Hints (A2)

This method is implemented by the TalkingGuideDisplay object described previously in the System Description chapter. It is based on the Spatialized Audio Display (A1), but is augmented to provide spoken assistance when the subject begins navigation or wanders off course. It follows the analogy of a sighted companion helping the blind pedestrian in the real world, gently adjusting and correcting the traveler as they progress. Like A1, spoken identification is projected from the actual location on the tablet device periodically. More specifically, an announcement of "Location, location, location, ..." is projected from the target location. To not overwhelm the traveler, a pause is inserted between each announcement. In addition to this continuous feedback, a synthetic assistant's voice is heard when the subject is in either of two conditions: (1) starting navigation or (2) they have wandered off course. In both cases, the assistant's instructions repeat until the subject achieves the desired heading.

4.3.3 Spatialized Audio with Visual Feedback (A0)

This method was introduced in order to establish an upper bound for navigational performance. A subject receives spatialized audio (as in A1), and also monitors their performance via the evaluation system's graphical display. The visual feedback is presented as seen in Figure 3.6. Note, this condition is limited to sighted subjects only.

4.3.4 Varying Pitch (B1)

This method provides audio feedback which is dependent upon the subject's direction, relative to the optimal direction to the destination. If the subject is on course, a periodic high pitch tone is generated. If the subject turns away from the target location, the pitch of the tone is proportionally lowered. If the user turns so far that they are point directly away from the location, the lowest tone is heard. No discrimination is performed for directional error based on whether the error in direction is to the left or to the right of the target location.

4.3.5 Varying Pitch, using Silence for *On-Course* Performance (B2)

This method is a variation of B1. Unlike B1, the periodic tone is muted if the subject is *on course*. As the subject turns slightly away from the on course condition, the highest tone is heard. As the subject turns further away, the pitch of the periodic tones decrease, as in B1.

These five conditions provide the basis for specific research questions. These were summarized in Table 4.2.

4.4 Experiment Method

The custom designed taux system will be used to perform systematic observation of users performing a series of simulated wayfinding tasks. Demographic data is collected prior to the experiment trials. Quantitative data is collected within subjects using repeated measures. Subjective data about user preferences and impressions is collected via a post-experiment questionnaire (please see Appendix I).

In the follow-on dissertation work, Latin Squares will be utilized to eliminate ordering effects. A counterbalanced design was not used for the pilot study conducted and reported in this dissertation proposal.

4.4.1 Independent Variables

With the system, as implemented, many possible independent variables exist. Some are global, affecting all of the display methods. Others are specific, applying to only a specific method or a group of methods. For the experiment conducted, all of the independent variables were controlled by holding them constant, with the exception of the display method. Thus a single factor (with five levels) experiment was run. Two tables (Table 4.3 and Table 4.4) summarize the variables considered. Table 4.3 identifies the independent variable, its values and relevant characteristics. Table 4.4 identifies all other possible independent variables that have been constrained and held constant for this experiment. This table organizes these constraints by condition and provides detail about their settings and relevant characteristics.

Table 4.3 Independent Variable

Name	**Value(s)**	**Description/Notes**
Display Condition	A1,A2,A0, B1,B2	*This is the only variable allowed to vary in the experiment work described within.* These conditions are described in the Research Questions section.

Table 4.4 Experiment Constraints

Name	**Value(s)**	**Description/Notes**
Arrival Radius	750	In tablet units. This is the maximum distance from a waypoint that will be allowed for determination of an arrival condition. This value is also described as "capture radius" by Walker & Lindsay (2006)
Heading On Course Threshold	3 degrees	Threshold for an on course condition. On course is signaled for a heading error of any value less than 3 degrees.
Heading Off Course Threshold	5 degrees	Threshold for error condition. Error condition signaled for heading error greater than 5 degrees. Note, a warning state is signaled for heading error > On Course and < Off Course conditions.
Inter Observation Interval	190 msecs.	Used by Data Sampler. This the frequency at which observations are recorded for analysis. This value assumes a sampling overhead of 10 msecs, resulting in approximately 200 msecs update interval.
AnnouncerDisplay Sleep Interval	20 msecs.	Interval used to process incoming events. Used by AnnouncerDisplay in all conditions.
Sleep Interval for Tablet Location Queries	50 msecs.	Frequency of polling for puck location and direction.
Update Interval for Tablet Location Reporting	50 msecs.	Frequency of updates that are provided to the NavigationManager.
Conditions A0, A1 and A2		
Sleep interval	20 msecs.	Interval used to process incoming events. Used by JoalDisplay.
Scale	1300.0	This is the scale to use when mapping from taux's global coordinate system to Joal's coordinate system.
Conditions B1 and B2		
Sleep Interval	20 msecs.	Interval used to process incoming events. Used by MidiDisplay.
Note Velocity	100	Note's volume.
Note Duration	20 msecs.	Duration to play note.
Note Lower Bound	20	Note played when heading error is 180 degrees.
Note Upper Bound	90	Note number played when heading error is 0 degrees (Note, value is muted in condition B2).
Update Interval	333 msecs	Frequency to provide periodic notes to the NavigationManager.
Midi Channel Number	4	Valid range is 0-127.
Midi Note Number	108	Valid range is 0-127.

Several additional variables are captured during the experiment. These are not manipulated and therefore are treated as control variables. These are collected via the pre-experiment questionnaire and include: age, gender, education level, handedness, computer proficiency and hearing ability. Analysis comparing performance based on these variables is not planned, but could be considered later.

4.4.2 Dependent Variables

Several dependent measures were used to assess subject performance. A number of these were drawn from existing research in creating real world navigation environments for the visually impaired. These precedents measure the efficiency of travel time and distance-traveled. (Loomis, Golledge and Klatzky, 1998; Ross & Lightman, 2005). In a scaled environment, work by Walker and Lindsay (2006) used path length and efficiency of travel time. In this work, efficiency of travel time (time per scheduled unit of distance) and distance efficiency were both used. This work is similar to the prior research in which subjects were selected non-randomly and subjects may or may not have been blind. The argument for this selection is twofold. First, it can be argued that there is unlikely to be an audio navigation advantage or disadvantage in the general population so that random sampling of subjects is not needed except for the ability to hear within normal ranges. And, second, it can also be argued that blindfolded subjects who can normally see are unlikely to behave differently in the audio navigation tasks than visually impaired subjects. If anything, the blindfolded subjects are likely to do somewhat poorer than visually impaired subjects because of their lack of experience in navigating without sight.

Existing research examples also monitor and measure a user's navigational error while performing experiment tasks. Ross and Lightman measure navigational error in a

2D plane, in a manner consistent with what will be done in this experiment. taux measures planar veer, which is similar to the linear measures used by Ross and Lightman. Marston, Loomis, Klatzky, Golledge & Smith (2006) enumerate errors descriptively, by and describe each error individually. As stated with distance and time measures, the user populations studied in the cited works are similar in demographics and attributes. taux also introduces a new measure, angular veer, which measures the directional error experienced by users. This measure is taken from research which measures hand eye coordination in a two-handed selection task (Fitzmaurice and Buxton, 1997). Both planar and rotational errors are used in this study.

4.4.2.1 Description of Dependent Variables. The following scenario will be used to describe the dependent variables. Consider a subject, navigating a trivial path as illustrated in Figure 4.1.

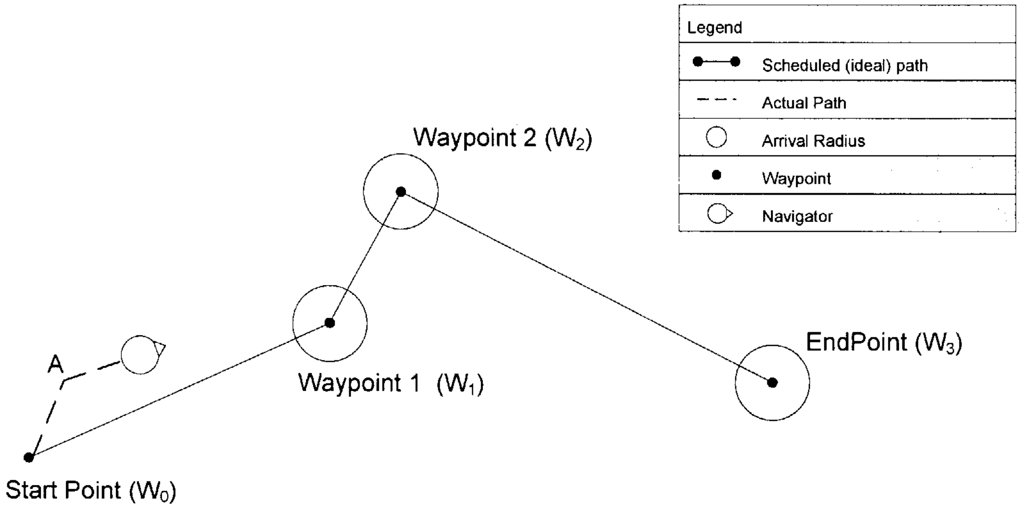


Figure 4.1 Subject navigating along a trivial path.

At the outset, the subject navigates to the starting point (W_0). Once arriving, taux' feedback is manipulated to display the location of Waypoint 1 (W_1). The subject doesn't proceed directly to W_1, but instead, follows a course that leads to point A. At point A, the subject adjusts direction and then proceeds towards point W_1. The subject can be observed in the figure navigating from A to W_1, pointed towards W_1. Figure 4.2 represents the next steps in the navigation.

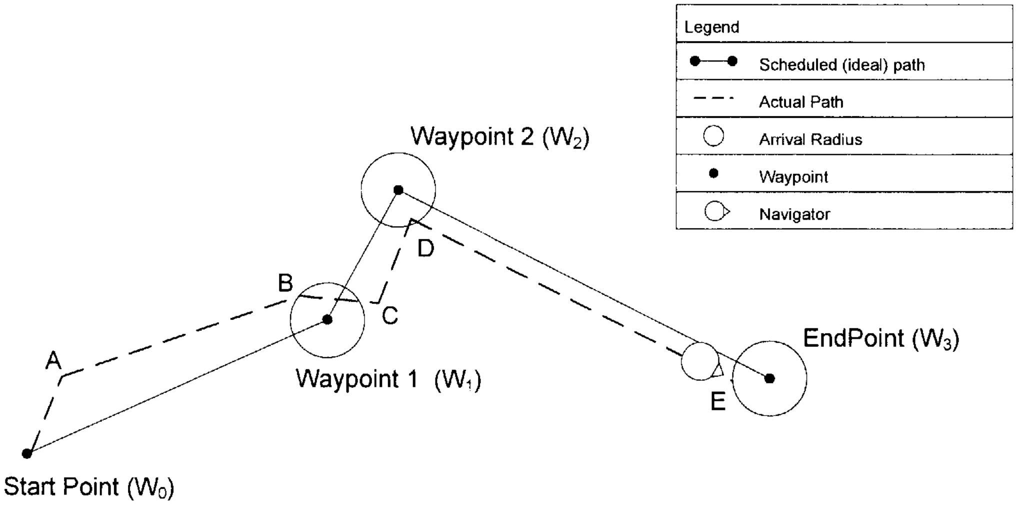

Legend
Scheduled (ideal) path
Actual Path
Arrival Radius
Waypoint
Navigator
Waypoint 2 (W2)
D
B
C
A
Waypoint 1 (W1)
EndPoint (W3)
E
Start Point (W0)

Figure 4.2 Subject completing trivial navigation.

Once the subject nears W_1, their location is analyzed and tested to see if they are within a predefined distance of W_1. This distance, the arrival radius (previously described as an experiment constraint), is shown and graphically exaggerated in the figure. Once they have satisfied the arrival condition, the system's output is updated to reflect the next waypoint (W_2). In this example, the subject visits points C, D and E while traveling towards W_2 and W_3.

4.4.2.1.1 Completion Time. Completion time is chosen because it reflects a real measure of the needed performance of any navigation aid. It takes too long to get to a destination, then the navigation aid is not useful. However, since the subsequent statistical analysis is performed within subject and using different travel paths for different conditions, this measure will not be used directly but will be used to calculate time per unit of scheduled distance (or time/unit distance).

Completion time measures the time it takes for the subject to travel from the start point (W_0) to the satisfying the arrival condition for the endpoint (W_3). In this example, that time is determined when the subject reaches point E. This time will be used to determine time efficiency in the subsequently described dependent measure. Since Completion time and time/unit distance are highly correlated, only time/unit distance will be carried forward through the statistical analyses.

4.4.2.1.2 Total Distance. The total distance is measured by summing the distances of each linear segment traveled by the subject. In the trivial example provided, this sum would be the total of segments W_0->A, A->B, B->C, C->D and D->E. Since the subsequent statistical analysis is performed within subject and using different travel paths, this measure will not be used directly but will be used to calculate a normalized distance efficiency. This measure is not recorded continuously, but is done so by sampling as described previously in the experiment constraints. In the studies performed, the sampling frequency was approximately 200 milliseconds.

4.4.2.1.3 Distance Efficiency. This measure represents the ratio of the total distance traveled to the scheduled path distance. This measure is calculated to adjust for comparisons made within subject and with different data paths in different conditions.

In the trivial example, the total distance traveled is the length of the dashed line and the scheduled distance is the length of the solid line. A distance efficiency of 1.0 would be ideal, describing a traveled path that perfectly followed the scheduled path.

4.4.2.1.4 Time / Unit Distance. Time per unit distance is chosen because as in completion time, it reflects real measure of the needed efficiency of the navigation aid. It takes too long to get to a destination, then the navigation aid is not useful. Time per unit distance adjusts total time to compensate for differing path lengths used in multiple conditions for the same subject.

In the example provided, the time per unit distance is determined by calculating the ratio of the completion time divided by the scheduled path length, which is represented by the solid lines in the figure.

4.4.2.15 Planar Veer. Planar veer is chosen as a measure because it measures the amount of extra effort the subject must go through in the navigation because of the imprecision of the feedback. It also represents the potential for other types of navigational difficulties because veering from the path may put the navigator into the territory that is dangerous or inconvenient, e.g., the street or mud.

Planar veer is determined as follows. Consider Figure 4.3. At any given point in time, a subject may be some distance away from the scheduled path. Optimally, they will be coincident with the path, and the corresponding planar veer will equal zero. More commonly, they will be somewhere off the scheduled path, and the veer distance will be a positive value representing the minimum distance between the subject and the scheduled path. Like total distance, the planar veer is sampled on a frequent basis. For subsequent analysis, all observations of planar veer for a given trial are averaged and then the average value is used in analysis.

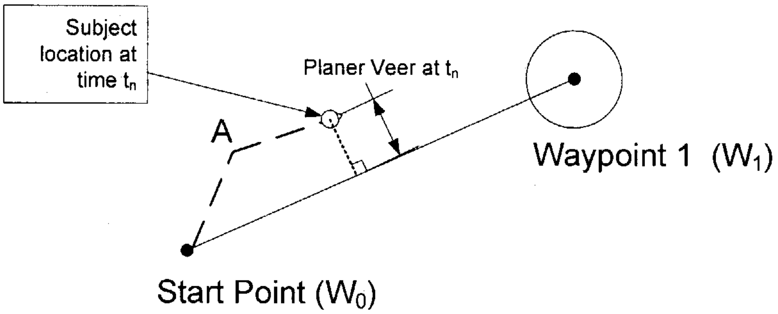


Figure 4.3 Illustrating planar veer.

4.4.2.1.6 Angular Veer. Like planar veer, angular veer is a measure that represents extra effort imposed on the navigator. It does, however, capture error that may be missed by the planar veer measure. Consider a navigator, who is directly on the scheduled path but pointed in the wrong direction. They would exhibit a planar veer value of zero; however, it is evident that they are significantly disoriented. Figure 4.4 illustrates the measurement performed.

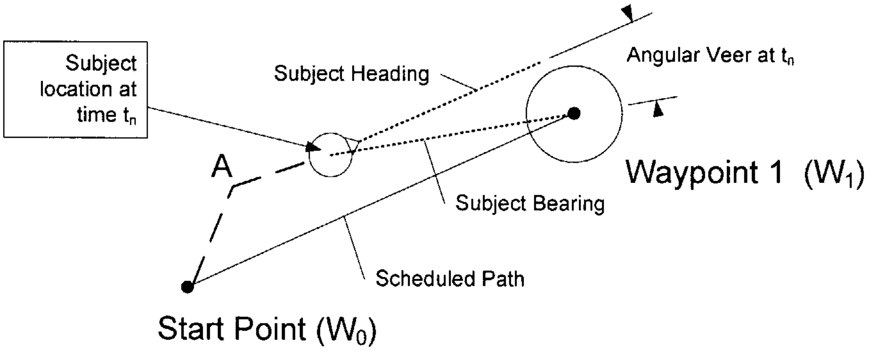

Subject location at time t_n
Subject Heading
Angular Veer at t_n
A
Waypoint 1 (W_1)
Subject Bearing
Scheduled Path
Start Point (W_0)

Figure 4.4 Illustrating angular veer.

In Figure 4.4, it can be seen that the angular veer is determined by calculating the angular distance between where the destination is relative to the subject (Subject Bearing) and where the subject is pointed to (Subject Heading). Like total distance and planar veer, angular veer is sampled on a periodic basis. And as in planar veer, the values collected during a trial are averaged and then this value is used in subsequent analysis.

4.4.2.2 Dependent Variables Summary. The following table summarizes the dependent variables used in this study:

Table 4.5 Dependent Variables

Description	Units	Type	Description
Completion Time	Milliseconds	Interval	Overall time recorded for task
Time/Unit Distance	Milliseconds /tablet unit	Ratio	Completion Time normalized to scheduled path length
Total Distance	Tablet units	Ratio	Overall distance traveled in task
Distance Efficiency	-	Ratio	Ratio of Total Distance to Ideal (scheduled path) distance
Planar Veer (Off Target Error, OTE)	Tablet units	Ratio	Distance between subject location and nearest point on scheduled path
Angular Veer (Heading Error, HE)	Radians	Ratio	Angular distance between heading and bearing angles of subject

Note: all distances are in tablet system coordinates (2540 tablet units = 1 inch)

4.4.3 Apparatus

The apparatus used constructs a virtual environment for navigation tasks. In this virtual environment, the participant assumes a first-person perspective in a virtual 2D space via a puck device atop a digitizer tablet. The virtual environment and its features are mapped onto the Wacom tablet's digitizing area. The main feature for navigation is a route, which is a series of waypoints. At any point in time, only one waypoint is active. The waypoint will represent itself in the virtual space by one of the main conditions described previously in the Independent Variables and Research Questions sections.

Consider an example experiment session. The user is presented with a route. The initial waypoint, the route start point, is displayed via the active display mode (the main condition variable). Recall that the display is accomplished only through sound, no physical or graphical features appear on the tablet. To perform the experiment task, the participant rotates and moves the puck, navigating toward the route's start point. Upon arrival, three beeps are heard, signaling the event. The active waypoint is now indexed to the next location in the route, the audio display changes to reflect the new destination. Experiment measurement data (time, distance, veer, etc.) are now recorded. The navigator follows the audio display and navigates the puck to the next waypoint. On arrival, a single beep is heard, and the audio display is updated to the next waypoint location. The navigator follows a similar course of action. This series continues until the route is completed. Once the final waypoint is achieved, recording of dependent variables is stopped. The captured data is recorded to disk for subsequent analysis.

A more thorough description of the system apparatus can be obtained in the Chapter 3.

4.4.4 Participants

Initial experimental apparatus design and feedback was provided by informants. These informants have been contacted through personal contacts of the advisor and this researcher. This feedback was used to refine system operation prior to the pilot study. These informants included two sighted participants and one with significant visual impairment. Additionally, informal walkthroughs were performed with approximately ten to fifteen sighted users and approximately ten to fifteen blind users.

Subsequently, for the pilot study, participants were identified through non-random means. Purposive sampling was performed through personal and professional contacts of this researcher and the thesis advisor.

The plan is to perform the next round of experiments with sighted subjects. The rationale for this choice is that blind users will bring variability based on the level of their impairment, and that sighted users will be more uniform. As a sample, sighted users will be less sensitive to the suggested variability. The sighted users will also be 'situationally blind', since navigational features are not visually exposed through the tablet interface. It is recognized that as the next round precludes blind users, the credibility of this work may be challenged by some in the accessibility community. But, based on the suggestions of the committee member active in this research area, the risk is identified and accepted and the work will go forward.

Participants will continue to be identified through non-random means. Purposive sampling will be performed through personal contacts. As before, personal and professional contacts of the thesis advisor and this researcher will be utilized.

For reasons of practicality, the subjects will live and/or work in the Northern New Jersey area. Experiment sessions can occur either at NJIT or at the location of participant. This flexibility is provided and maintained due to the transportation limitations that future blind participants may encounter due to their impairment.

There are several reasons why the non-random selection of subjects and the low number of subjects (10) were believed to be acceptable in this research. First, the phenomenon being measured is a psychophysical not a social behavior phenomenon. Therefore, it is not expected that there will be wide ranging differences in how audio is heard and interpreted. We would expect some differences between sighted and blind subjects because blind subjects are likely to use audio cues in everyday life to help interpret their environment whereas sighted suibjects are relatively unskilled in using these cues. The small number of subjects is supported by a similar argument. The effect sizes of the results are expected to be large, that is, some audio will clearly be better at guiding subjects than others. Also, a large amount of variance in how individuals hear one audio queue vs. another is not expected in experiments that are akin to psychophysics experiments. It is assumed in these types of experiments that individuals come with relatively similar cognitive and perception apparatus, thus, low N's are commonly used. In addition, the replication of the tasks and consistent behavior within each task demonstrates this. This philosophical argument is discussed in more detail in Todman and Dugard (2001).

Approximately thirty informants were used during the pre-Pilot phase. Eight sighted participants were studied during the pilot phase. Ten sighted and/or blind subjects will be studied during the thesis phase of this research.

No monetary compensation is provided for participation. Blind participants are offered consultation assistance with setup and usage of NJIT's AudioBrowser RSS news reader tool as compensation for their participation.

4.4.5 Subject Demographics for Pilot Study

The pre-questionnaire was administered to collect information about subjects. Subjects were asked questions about their age, gender, education level, computer proficiency and hearing ability. The follow paragraph summarizes their responses.

Eight subjects participated in the pilot study. Of these, two were female and six were male. All were right handed. All subjects had a college level education, with four at an advanced level. The average age was 42.5 years. These subjects reported computer use of 1-14 hours per day, with an average of 8.75 hours per day. These participants reported computer experience ranging from 13 to 30 years, with a mean value of 20.125 years. Allowing for corrected vision, six subjects exhibited 20/25 vision. Of the two subjects that did not exhibit 20/25 vision, one has 20/30 and the other has 20/15 vision. One subject reported hearing loss.

4.4.6 Procedure

Before any experiments were performed, an application for human subject testing was submitted to NJIT's Internal Review Board. The application was approved by the IRB. The application is included in this thesis as Appendix B.

Prior to conducting the experiment, the investigator consults a preparation checklist (please see Appendix L). Confirming all the items on this checklist are complete prior to a session ensures that all the steps of the experiment are conducted consistently.

Once the experiment begins, the investigator follows the steps detailed within the Investigator's Record Sheet. This record sheet also contains a checklist. The complete record sheet can be found in Appendix A. Using the checklist from the record sheet as guide, the steps for the experiment are detailed here as follows. Steps 0 through step 2:

0) ____ Perform headset check - record volumes for each channel
1) ____ Check Windows settings for volume and balance
2) ____ Disable virus scanning on computer

Steps 0 through 2 are intended to establish a common starting point prior to conduction the actual experiment. These steps can be performed prior to the subject's arrival or while the subject performs steps 3-4 independently (a description of steps 3-4 follow). If the subject is visually impaired, and steps 3-4 are performed in parallel, a sighted companion will read the introduction and consent form to the subject. Next, steps 3-5 are followed:

3) ____ Read *Study Introduction* to the subject
(introduction text can be found in Appendix A)
4) ____ Execute consent form
(please see Appendix C)
5) ____ Pre-questionnaire
(either Appendix G or Appendix H, as appropriate for sighted and non-sighted users)

Step 5 uses different questionnaires based on the subject's level of impairment. At this point, the preparation for the experiment has been completed. The investigator and subject now begin the protocols for the actual experiment. The individual conditions are taken in turn; each one is preceded with introductory instructions and a number of practice sessions. The detailed instructions for each condition are found in Appendix F. The corresponding item in the record sheet checklist appears as follows:

6) ____ Subject training script and instructions for the experiment session

At this point, the quantitative portion of the experiment is performed and completed. Several items are remaining. The subject fills out a post-questionnaire which captures their preferences about the system. Additionally, several questions are asked to gather the subject's opinions about potential generalizability. Finally, the subject is thanked and presented with the debriefing sheet. The corresponding checklist items for these steps are presented as follows:

7) ____ Subject post questionnaire
(Included as Appendix I)
8) ____ Subject debriefing form
(*Included as* Appendix J)
9) ____ Arrange to get copies to subject

The checklist also contains space for data collected during each trial. This data includes any questions that the subject had within a specific trial as well as any qualitative observations that the investigator feels are appropriate.

CHAPTER 5

RESULTS OF THE TEST EXPERIMENT

This section will report on the analysis of the experiments that were described in Chapter 4. The reader should again note that the hypotheses put forth, the experiments conducted and the analyses carried out do not constitute the key focus of the thesis but rather only an answer to one of the research questions, that is: can the taux system be used to explore auditory feedback in navigation. As such, there will be two analyses, first of the experiment results and second of the ease in which the experiment was built and carried out and the flexibility of the taux system for varying and adjusting audio for navigation feedback. This second analysis will thus constitute a case study of the experiment.

The next section of this chapter addresses the first research question of the thesis by examining overall subject navigation in the experiments. The sections which follow then address the specific hypotheses promulgated in the experiment description in Chapter 4. First, the descriptive statistics are presented followed by a check on the assumptions that can be made on the distributions of the data collected in the study. This is followed by comparative statistical analyses which focuses on which of the auditory feedback conditions worked best for the virtual navigation. Issues with learning are discussed and improvements suggested for controlling this variable. A short summary leads the reader into Chapter 6 which discusses in depth the research questions posed by this thesis.

5.1 Subjects' Path Data

The initial research question of this thesis was: Does the transformation of our navigation task to one of path navigation on an electronic tablet effectively simulate the intended navigation task?" Although no work was done in the thesis to compare a real world navigation task to navigation on the tablet, it was argued that if subjects are able to navigate on a virtual path using taux, that viable navigation on paths that scale to real world paths is at least representative of the real world task. Figures 5-1 and 5-2 display representative plots of a subject's traversal. These figures are for the same subject's paths collected from two different conditions. The thick black line indicates the ideal path; the blue dashed line indicates the recorded subject traversal. The dashed circles indicate an arrival radius of the subject for each waypoint. The arrival radius is used to signal a waypoint arrival event. Once the subject arrives anywhere within the circle, the event is signaled. Figures 5-1 and 5-2 indirectly indicate the subject's veer error. No accommodation is made to display the time measurements or the angular veer. These will be summarized and discussed in Chapter 6.

The figures contained in Appendix P (Figures P-1 through P-5) present all of the subjects' path traversals in each of the five conditions. Different colors are used to represent each subject; the subject identifier can be referenced in the legend. The data in these tracking plots is discussed in more detail in the next chapter.

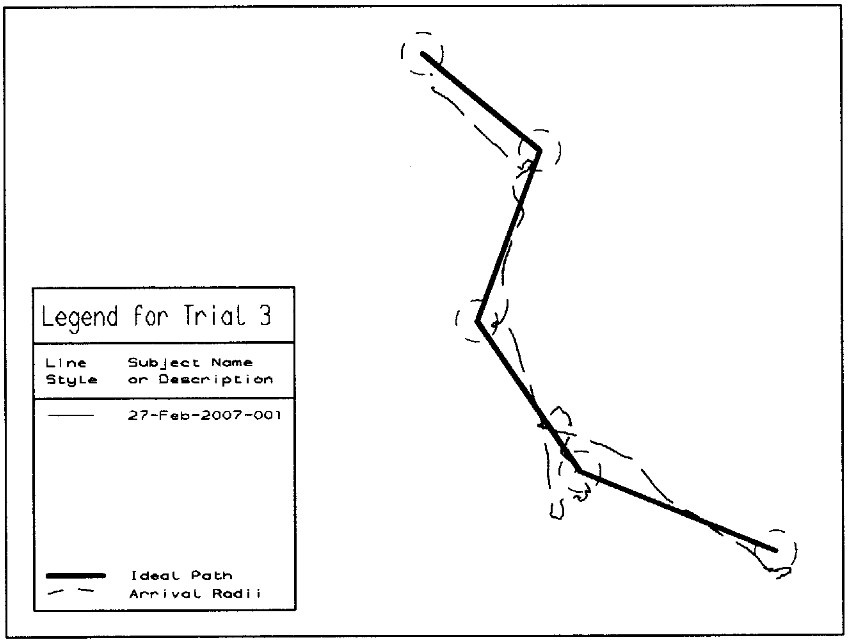


Figure 5.1 Subject navigating in condition A1. While not optimal performance, this subject was able to perform the task.

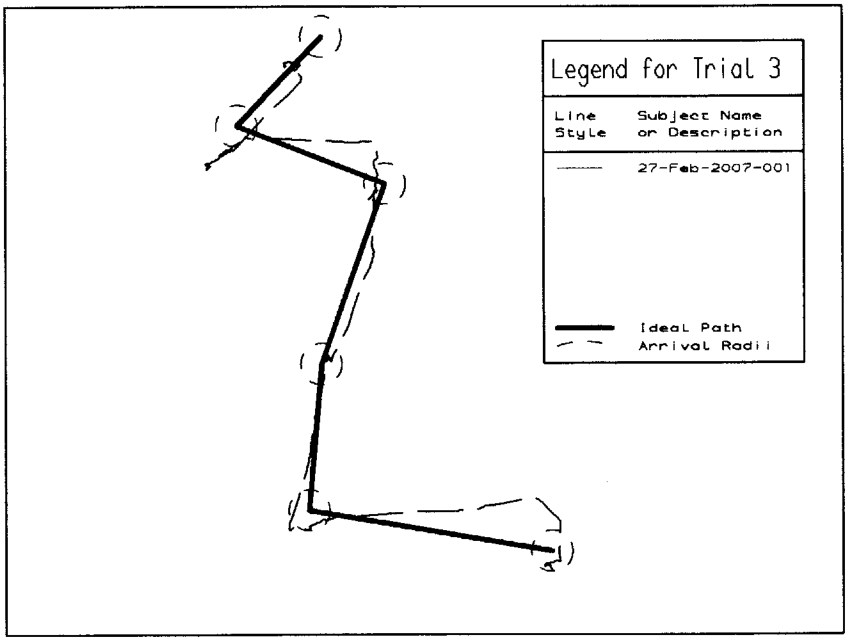


Figure 5.2 Subject navigating in condition A2. This is the same subject that was shown in Figure 5.1. Note that the navigation is improved in this condition.

5.2 Descriptive Statistics

This section provides a summary of the descriptive statistics for the quantitative data collected during all experiment trials. The R (http:// www.r-project.org) statistics package was used to perform the analyses. Table 5.1 presents the means, standard deviations and ranges measured for each of the dependent variables in the study. The following list presents a quick review of these variables and the shortened names used to describe them in the statistical analyses which follow.

5.2.1 Description of Terms

The following terms are used in the analysis of the data.

SubjID	a unique identifier representing each subject
Group	the condition, one of A0, A1, A2, B1, B2 A0 = spatialized audio with visual feedback. A1 = Spatialized audio. A2 = Spatialized audio with hints. B1 = varying pitch B2 = varying pitch with silence during on-target condition
DataFile	The data file used for the specific trial. Each datafile contains a start point and 3-5 locations that make up a route.
TotalDist	The total distance traversed by a subject, subject to approximation through periodic sampling. Sampling rate is 200 msecs during the experiment. These are reported in global coordinates for the taux system (currently tablet units)
DistRatio	The ratio of the distance traveled divided by the ideal distance if the route were perfectly traversed.
AvgOTE	The average of all 'off-target' distances collected during the trial. These are sampled once every 200 msecs during the experiment and reported in global coordinates for the taux system (currently tablet units)
AvgHE	The average value of all heading errors recorded during the trial. These are sampled once every 200 msecs during the experiment and reported in radians.
T/UD/WP	Time per unit distance. Measures the time the subject took to traverse a particular trial. Since trial routes differ in length, the time is divided by the route length to normalize for comparison. This variable is reported in msecs/distance (distance in taux global coordinates.)

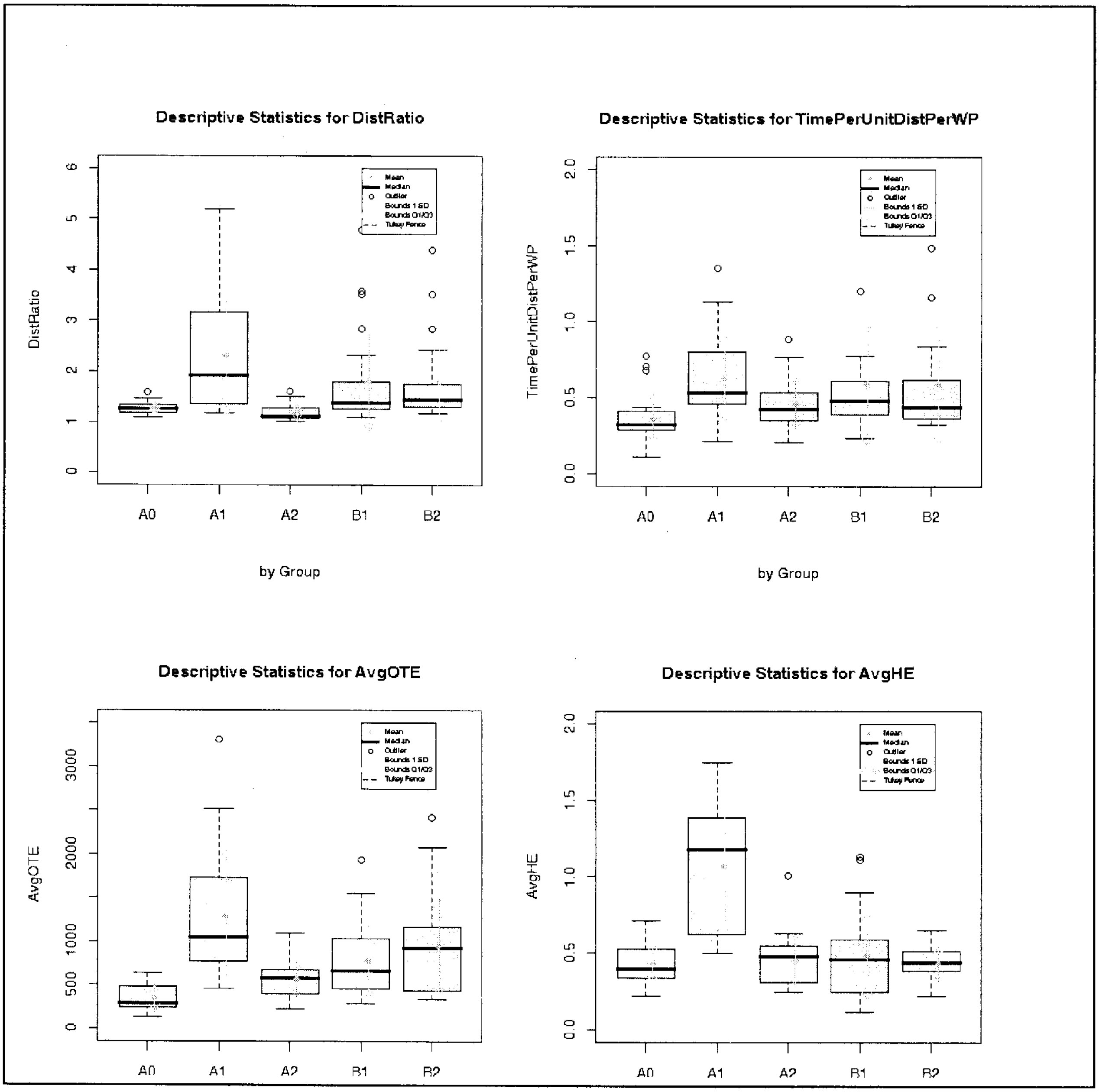
Table 5.1 Descriptive Statistics for Dependent Variables in Audio Feedback Experiment

Group	Table of Means					
Spatialized Audio + Visual Feedback (A0)	**Variable**	**N**	**Mean**	**Std. Dev.**	**Min**	**Max**
	DistRatio	24	1.267	0.124	1.093	1.580
	AvgOTE	24	344.90	151.48	127.47	635.98
	AvgHE	24	0.436	0.132	0.218	0.717
	T/UD/WP	24	0.365	0.163	0.111	0.774
Spatialized Audio (A1)	**Variable**	**N**	**Mean**	**Std. Dev.**	**Min**	**Max**
	DistRatio	21	2.327	1.200	1.171	5.195
	AvgOTE	21	1286.3	766.88	454.82	3312.9
	AvgHE	21	1.070	0.437	0.500	1.747
	T/UD/WP	21	0.632	0.291	0.213	1.356
Spatialized Audio + Hints (A2)	**Variable**	**N**	**Mean**	**Std. Dev.**	**Min**	**Max**
	DistRatio	24	1.186	0.166	1.013	1.619
	AvgOTE	24	567.063	207.88	232.20	1090.9
	AvgHE	24	0.456	0.170	0.248	1.010
	T/UD/WP	24	0.462	0.175	0.206	0.887
Varying Pitch (B1)	**Variable**	**N**	**Mean**	**Std. Dev.**	**Min**	**Max**
	DistRatio	22	1.804	0.993	1.100	4.774
	AvgOTE	22	774.29	427.97	285.33	1939.4
	AvgHE	22	0.485	0.285	0.114	1.131
	T/UD/WP	22	0.591	0.403	0.237	2.154
Varying Pitch w/Silence (B2)	**Variable**	**N**	**Mean**	**Std. Dev.**	**Min**	**Max**
	DistRatio	24	1.790	0.796	1.182	4.398
	AvgOTE	24	944.02	560.22	335.24	2415.8
	AvgHE	24	0.436	0.117	0.221	0.650
	T/UD/WP	24	0.591	0.389	0.326	1.882

The following plots (Figure 5.3) display group means for each of the dependent variables. Several other descriptive statistics are displayed. The plots combine these statistics using a standard Tukey "Box and Whisker" plot. The following table (Table 5.2) provides a description of each value used. As can be seen from the plots, condition A1, spatialized audio without hints stands out from all of the other conditions. Since this condition is being used as a baseline, performance on the other conditions which exceed this condition are considered better performances. Recall that condition A0 integrates visual feedback, and provide an upper limit on performance since subjects have the added information provided through the visual sense.

Table 5.2 Description of Plotted Values

Value	Description
Mean	Mean for the dataset.
Median	Median for the dataset.
Outlier	Any point that falls outside the range of $Q_{0.25}$ - 1.5 x IQR and $Q_{0.75}$ + 1.5 x IQR. The inner quartile range (IQR) is defined as $Q_{0.75}$ - $Q_{0.25}$.
Bounds 1 S.D.	Line with arrows display the extents of 1 Standard Deviation
Bounds $Q_{0.25}/Q_{0.75}$	The shaded box bounds the data which falls within the second and third quartiles. The lower edge is at Q1, the upper edge is at Q3.
Tukey Fence (or Whisker Line)	The fence line typically found on Tukey plots. These lines identify the smallest and largest values in the dataset that do not meet the outlier criteria.



5.3 Summary Plots for Descriptive Statistics of Dependent Variables

5.3 Inferential Statistics

5.3.1 Correlation and Effect Size

Initially, it was suspected that the dependent variables (DistRatio, AvgOTE, AvgHE and TimePerUnitDistPerWP) would be highly correlated. If they were independent, one could run simple statistical tests on the data looking at the impact of each dependent variable separately. Because this is unlikely, the appropriate comparison of the audio feedback conditions will probably need to be carried out using a multivariate analysis of variance. However, this approach is not as powerful as using a simple analysis of variance on each dependent variable. To determine if a multivariate analysis of variance is unnecessary, we conduct a correlation analysis between the dependent variables.

The Pearson product-moment correlation is used to find the strength of the relationship between variables. The results of this analysis are summarized in Table 5.3.

Table 5.3 Pearson Product-Moment Correlation Coefficients Between Dependent Variables

Note: Significant Values in Boldface

Dependent Variable	DistRatio	AvgOTE	AvgHE	TimePerUnitDistPerWP
DistRatio	1.00	**0.78**	**0.57**	**0.67**
AvgOTE	**0.78**	1.00	**0.65**	**0.58**
AvgHE	**0.57**	**0.65**	1.00	**0.21**
TimePerUnitDistPerWP	**0.67**	**0.58**	**0.21**	1.00

DistRatio and AvgOTE are highly correlated (ratio = 0.78), and moderate correlations exist between AvgHE and either AvgOTE or DistRatio (0.65 and 0.57 respectively). TimePerUnitDistPerWP is moderately correlated with DistRatio and AvgOTE measures (0.67 and 0.58, respectively). All of the measures except the TimePerUnitDistPerWP are measures of accuracy, which is how well the subject follows the path. The TimePerUnitDistPerWP measure is an attempt to capture how much time a subject spent in the navigation. Accuracy will affect this somewhat because subjects will travel more distance and therefore take more time, but unlike the usual speed accuracy tradeoff, this relationship is not apparent in the data. Consulting a table of critical values for r, any value over .423 is considered significant ($r_{alpha=0.05,\ n=116}=0.182$). Significant values are represented in boldface type in Table 5.3.

An additional indication of the strength of the association between variables is the effect size. Table 5.4 reflects the effect size of the group for each of the dependent variables. Both the large effect sizes and the significant correlations indicate that a multivariate analysis of variance needs to be run to determine the statistically significant results of the different audio feedback conditions.

Table 5.4 Effect Size of Dependent Variables

variable	$SS_{variable}$	SS_{Total}	eta
DistRatio	19.30	84.41	0.48
AvgOTE	11649877	35998427	0.57
AvgHE	6.58	13.48	0.70
TimePerUnitDist	1.15	11.07	0.32

5.3.2 Normality

Several other assumptions for MANOVA are tested, based on the data collected. Violations for the assumptions of normality are checked. In all but one condition violations exist. Table 5.5 summarizes the findings:

Table 5.5 Summary of Probabilities, Tabulated by Condition and Dependent Variable, for Shapiro-Wilk Statistic. Values significant at the 95% Level are Marked in Bold.

	A0	A1	A2	B1	B2
DistRatio	0.245	**0.009**	**0.001**	**<0.0001**	**<0.0001**
AvgOTE	**0.043**	**0.014**	0.231	**0.030**	**0.010**
AvgHE	0.653	**0.015**	**0.005**	**0.044**	0.492
Time/UD/WP	**0.006**	0.214	0.130	**<0.0001**	**<0.0001**

In order to perform the desired paired comparisons, and since both multivariate analysis of variance and parametric techniques are excluded due to lack of normality, a non-parametric approach is pursued. The Mann Whitney statistic (U) is calculated and associated probabilities are calculated to draw inference about the differences observed between the group means. This distribution-free approach allows substitution of order statistics for the collected data to support assertions. Table 5.6 provides a summary of the U statistic and associated probabilities for a one-tailed two sample approach. The R source code for this analysis is included in Appendix N. It can be seen that general support for the planned comparisons exists; the departures will be discussed in the next chapter. It should be noted that the significant correlations between the dependent variables suggest that a multivariate non-parametric test be run rather than these individual comparisons. However, the development of these techniques is relatively new and their usage has not been investigated in a wide variety of settings. More will be said in the discussion section.

Table 5.6 Paired Comparisons Using Mann Whitney Statistic. Values Displayed are U Statistic and Corresponding Probability (p), with Significant Values Shown in Bold at 95% Level.

	A2 v. A1	B2 v. B1	A0 v. A1	A0 v. A2
DistRatio	**459** **<0.0001**	219 0.840	**420** **<0.0001**	165 0.995
AvgOTE	**433** **<0.0001**	219 0.840	**483** **<0.0001**	**474** **<0.0001**
AvgHE	**473** **<0.0001**	281 0.360	**475** **<0.0001**	292 0.472
Time/UD/WP	**347** **0.015**	288 0.304	**410** **<0.0001**	**396** **0.013**

With the inferential statistics and probabilities, the original experiment hypotheses comparing performance can be revisited using the findings for the final experiment. Supported/unsupported status is identified for each of the hypotheses in Table 5.7. The results presented here will be discussed further in the next chapter.

Table 5.7 Support/Unsupported Status of Test Experiment Performance Hypotheses

Hyp.	Status	Description
H1		Subjects will perform better with the Talking Guide (A2) than with Spatialized Audio (A1).
H1a	**Support**	**Subjects will have a lower completion time when navigating with A2 v. A1.**
H1b	**Support**	**Subjects will have a better (lower) distance efficiency with A2 v. A1.**
H1c	**Support**	**Subjects will have a lower average veer (off target error, OTE) with A2 v. A1.**
H1d	**Support**	**Subjects will have a lower average angular veer (heading error, HE) with A2 v. A1.**
H2		Subjects will perform better with Visual Feedback (A0) than with A1 or A2. H2a – H2d considers A0 v. A1.
H2a	**Support**	**Subjects will have a lower completion time rate when navigating with A0 v. A1.**
H2b	**Support**	**Subjects will have a better (lower) distance efficiency with A0 v. A1.**
H2c	**Support**	**Subjects will have a lower average veer (off target error, OTE) with A0 v. A1.**
H2d	**Support**	**Subjects will have a lower average angular veer (heading error, HE) with A0 v. A1.**
H2		Subjects will perform better with Visual Feedback (A0) than with A1 or A2. H2e – H2h considers A0 v. A2.
H2e	Not Supported	Subjects will have a lower completion time when navigating with A0 v. A2.
H2f	**Support**	**Subjects will have a better (lower) distance efficiency with A0 v. A2.**
H2g	Not Supported	will have a lower average veer (off target error, OTE) with A0 v. A2.
H2h	**Support**	**Subjects will have a lower average angular veer (heading error, HE) with A0 v. A2.**
H3		Will Pitch w/Silence for on-course (B2) be better that pitch alone (B1)?
H3a	Not Supported	Subjects will have a lower completion time when navigating with B2 v. B1.
H3b	Not Supported	Subjects will have a better distance efficiency with B2 v. B1.
H3c	Not Supported	Subjects will have a lower average veer (off target error, OTE) with B2 v. B1.
H3d	Not Supported	Subjects will have a lower average angular veer (heading error, HE) with B2 v. B1.

5.4 Analysis of Learning Data

A primary assumption of a crossed, repeated measures design is that the subjects' performance will be uniform throughout the experiment. Stated in different terms, it is undesirable to have the subjects' performance improve during the trials due to learning or practice. Two aspects of learning and practice are of concern. At the widest scale, subjects may become more accustomed to any audio display and improve from condition to condition, independent of the actual display mode. This is an order effect. At a smaller scale, and *within* a particular condition, the subject may improve as they progress from trial to trial within that condition. Training and practice trials with each display mode are conducted to mitigate this narrower case, but it is unclear if the current training protocol is sufficient. In either case, this learning can have an impact on the control of the experiment and affect the statistical tests run. For example, performance in conditions that occur later in the experiment may be due to increased practice by the subject and not the condition. In the second case where learning might occur within a condition, it is possible that for a given condition, learning is at a different rate, thus affecting the overall performance of the subject in that condition, either making the condition look better or worse than it actually is. This section provides data collected that pertains to learning. This data will be further developed in the following Discussion of Results and Planned Research sections.

In the wider scale, it is recognized that an ordering effect may exist. If true, trials performed during an experiment session may exhibit improved subject performance as the overall session progresses. In order to control for this, a counterbalanced design can be applied to the experiment. This design consideration was omitted during the pilot study, but will be incorporated in the next study conducted for this research.

In the narrower scale, learning effects will exist within-condition if the training period is not sufficiently long. In one instance of the experiment, a subject commented that they felt as if they were still improving as they progressed through the trials. As described earlier in the procedure section, controls were implemented to assess the user's performance as they completed each practice case. TimePerUnitDistPerWP, more specifically, was compiled on a per-waypoint basis during practice and examined for a leveling effect. During the pilot study these controls were observed to be too coarse. To compensate, a subjective assessment of learning was applied by the investigator. In order to better understand the performance data and plan for the next phase of the experiment, the following plots were constructed (Figure 5.4). Of the four dependent variables, it is reasonable to consider only those that are collected continuously. TimePerUnitDistPerWP is removed from consideration since it is based on the ideal route or individual segment length (from waypoint to waypoint) and its meaning may be ambiguous while the subject is between these milestone points. DistRatio is eliminated for similar reasons, since its meaning would not be clear until the route has been completed. This leaves two others: off target error (OTE) and heading error (HE). These are plotted as a function of time. An example is provided in Figure 5.4. The lighter lines represent the values collected from one subject. The top row summarizes OTE, while the bottom row summarizes HE. In the bottom row's three panels, pronounced peaks are observed for HE. This is expected since a navigator's HE suddenly spikes immediately after arriving at a waypoint. In the top three panels, peaks have a different meaning. For OTE, these indicate that the subject has veered far away from the ideal path. The darker red lines are fit by applying a locally-weighted polynomial "lowess" regression (details at http://stat.ethz.ch/R-manual/R-patched/library/stats/html/lowess.html). The parameters for the *lowess* regressions used are set as: (1) smoother span (f) equal to 2/3 and (2) 'robustifying' iterations equal to three.

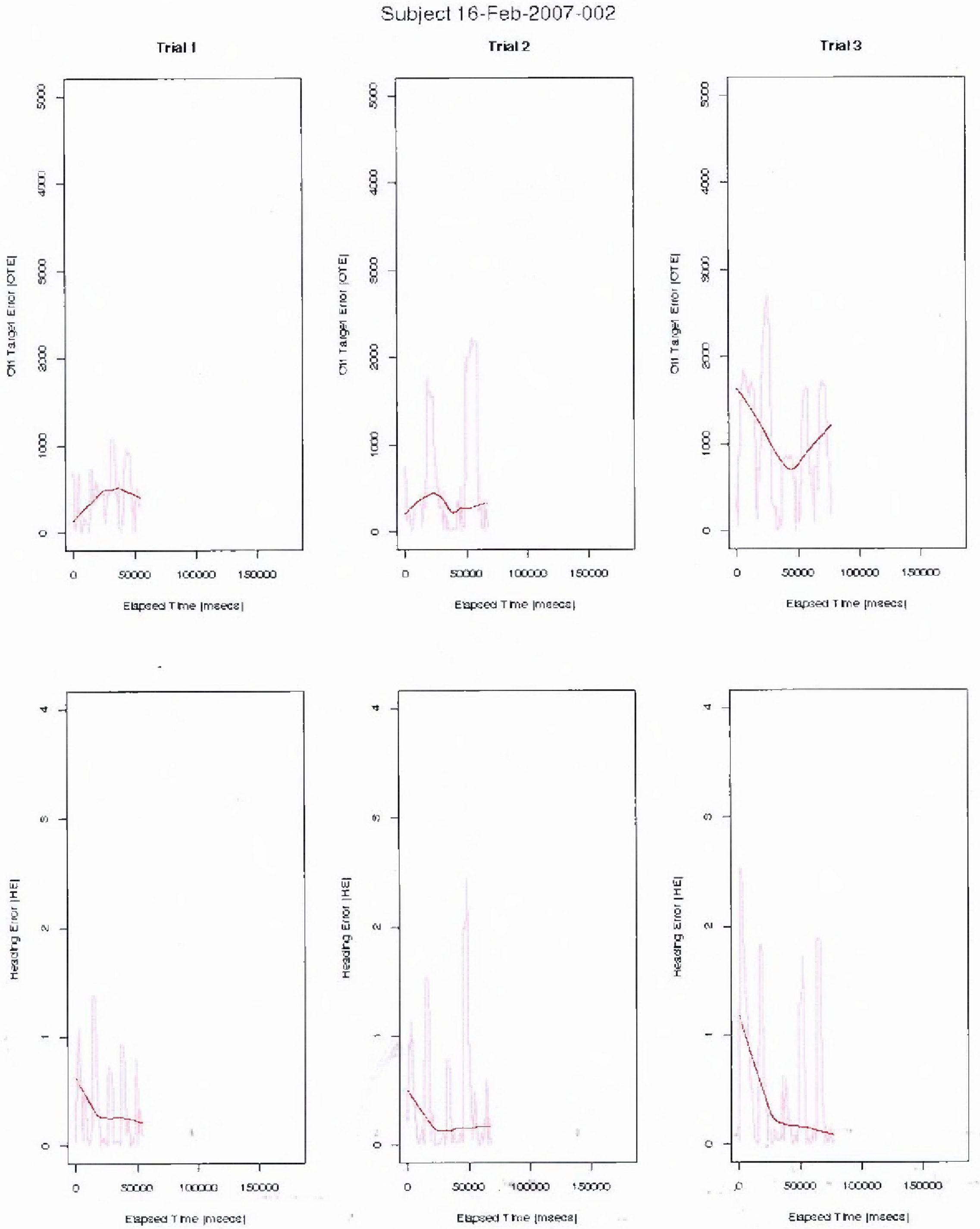


Figure 5.4 Example OTE and HE trends for a subject during one condition.

In the figures listed in Appendix Q (Figures Q-1 through Q-5), data for all subjects are included and plotted for each group. The copious underlying data has been suppressed for the purpose of legibility, while the regression lines are maintained for the purposes of comparison and analysis. The legend contains the mapping of each subject to its respective trend line.

5.5 Survey Results

Data about user preferences was collected in a post experiment survey. Table 5.8 summarizes both the descriptive and inferential statistics for this data. For survey questions one through six, the sample mean is provided. This value is compared in a one-sample test by comparison against the neutral response (a neutral response is equal to three, in both Type A or Type B scales. The Type A/TypeB scales used for each question and descriptions of each type are also listed in Table 5.8). The null hypothesis is tested to determine if the sampled mean is equal to a neutral response, and reject if the neutral response value falls outside the 95% confidence interval of the mean value for the data collected. In question seven, a similar approach is employed. Since question 7 utilizes only three possible responses, the one-sample test is applied by comparing the mean of responses with the middle state ('same', where the value is equal to two).

Table 5.8 Descriptive and Inferential Statistics for Qualitative Data Collected

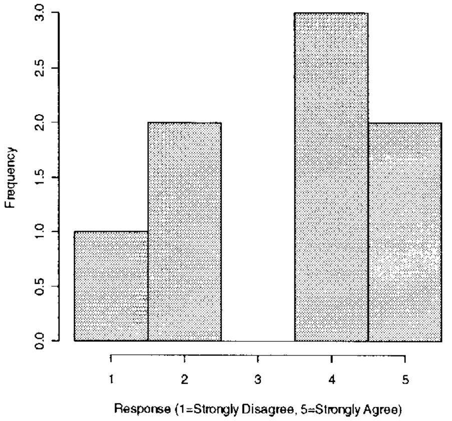
Q#	Question	Score Type	Average Score	t statistic	*p*
1	I preferred hearing a sound at the location versus the varying pitch sounds	A	3.4	0.70	0.50
2	When listening to varying sounds, I preferred silence to a high pitch when I was facing directly at the location	A	3.8	1.43	0.20
3	If I were lost in the woods, and all I had was a headset speaking "Location, location, ..." to guide me, it would help me	B	1.5	-7.94	<0.001*
4	If I were lost in the city and became disoriented, and all I had was a headset that played the voice speaking "Location, location, ..", to guide me, it would help me	B	1.9	-3.21	0.15
5	If I were lost in the woods, and all I had was a headset that played varying pitch sounds to guide me, it would help me	B	2.0	-3.27	0.05*
6	I feel that either of the demonstrated methods (varying pitch tone or sound at the location) could allow me to find my destination in the real world.	A	3.9	2.97	0.02*
7	How do you compare these methods to find destinations with you currently use for navigation in the real world?	C	2.4	1.16	0.29
8	Rank Spatial Audio	D	2.6		
8	Rank Spatial Audio w/hints	D	2.1		
8	Varying Pitch	D	2.8		
8	Varying Pitch w/Silence	D	2.5		

Note: * items significant at the 95% level

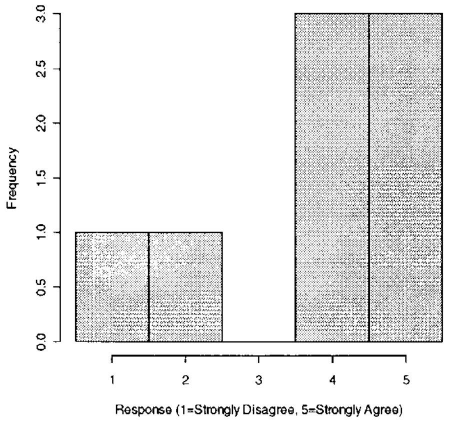
Score Type defined by:

A	1=Strongly Disagree, 2=Disagree, 3=Neutral, 4=Agree, 5=Strongly Agree
B	1=Very Much, 2=Somewhat, 3=Neutral, 4=Not Much, 5=Not at All
C	1=Better, 2=Same, 3=Worse
D	Ranked Value, 1-4. 1=Highest, 4= Lowest.

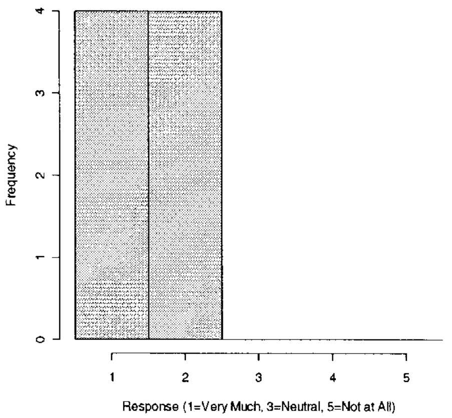
The following histograms (Figure 5.5) illustrate the distribution of the subjects' responses for questions one through seven.



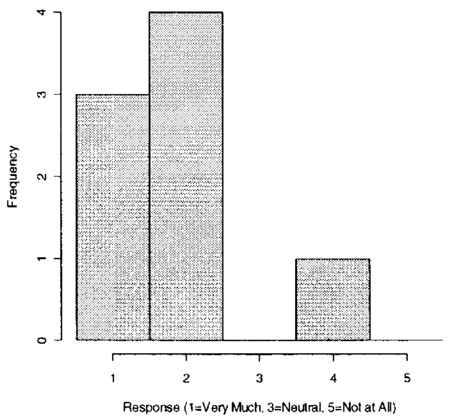
Question 1: I preferred hearing a sound at the location versus the varying pitch sounds



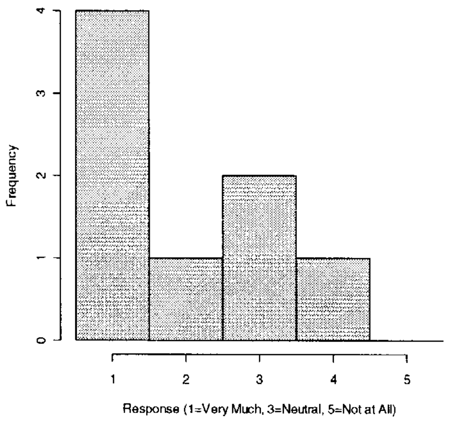
Question 2: When listening to varying sounds, I preferred silence to a high pitch when I was facing directly at the location



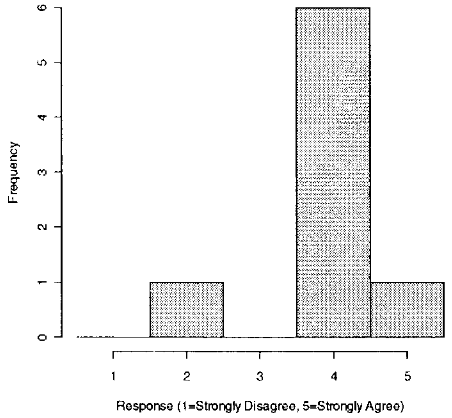
Question 3: If I were lost in the woods, and all I had was a headset speaking "Location, location, ..." to guide me, it would help me



Question 4: If I were lost in the city and became disoriented, and all I had was a headset that played the voice speaking "Location, location, ..." to guide me, it would help me ....



Question 5: If I were lost in the woods, and all I had was a headset that played vaying pitch sounds to guide me, it would help me ....



Question 6: I feel that either of the demonstrated methods (varying pitch tone or sound at the location) could allow me to find my destination in the real world.

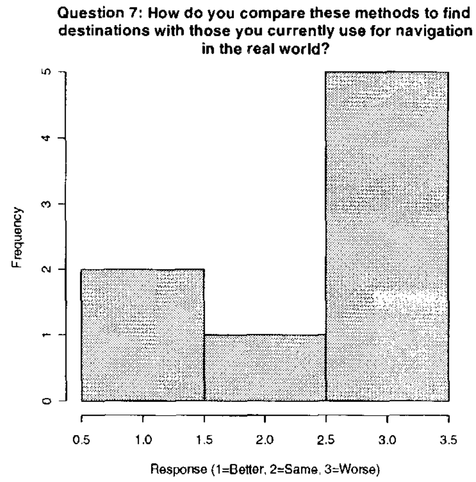


Figure 5.5 Subjects responses corresponding to their preferences.

When asked about preferred displays (Question 8), subjects ranked them in this order:

Table 5.9 Comparison of Means of User Preferences for Display Modes

Condition	Description	Rank Sum	Score (Mean Rank)
A2	Spatialized audio with Hints	17	2.125
B2	Varying Pitch with Silence	20	2.5
A1	Spatialized Audio	21	2.625
B1	Varying Pitch	22	2.75

The means provided suggest that subjects prefer B2 to B1, and also prefer A2 to A1 as initially hypothesized. It should be noted however, that these comparisons are not statistically significant. The method used to analyze significance for rank ordered selections (without ties) is taken from Quandt (http://www.liquidasset.com/corsica.htm). A detailed summary of the analysis method is contained in Appendix S. An alpha level of 0.05 was used. The following hypotheses for the post-interview measures are re-visited to determine if user preferences are consistent with the hypothesized predictions.

Table 5.10 Hypotheses and Reject/Support Status for User Preferences

Hyp.	Status	Description
H1e.	Support*	Subjects will prefer Talking Guide (Spatialized Audio with hints, A2) to Spatialized Audio (A1).
H3e.	Support*	Subjects will prefer Pitch w/Silence (B2) to Varying Pitch (B1).

* not statistically significant

5.6 Chapter Summary

This bulk of this chapter presented the detailed statistical analysis of the data collected in the experiment described in Chapter 4. Overall, it found significant differences between some but not all audio feedback conditions. It did also find that some of these differences were large suggesting that two of the conditions tried were better than the others, which is that spatialized audio with hints is better than spatialized audio without hints and that spatialized audio with visual feedback is better than spatialized audio. This suggests that multiple audio signals giving information about different aspects of the navigation are readily processed by navigators and are better than combining the information into a single signal. The next chapter discusses the results of the experiment and also what the experiment implies in terms of the evaluation of taux as a prototyping tool for studying audio feedback.

CHAPTER 6

DISCUSSION OF RESULTS FROM THE TEST EXPERIMENT

This chapter will consider both the original research questions and the results presented in the preceding chapter. Where possible, evidence to support the original hypotheses is provided. Several additional discussions follow. A discussion of validity is offered, considering both the developed apparatus and the experimental methods. Next, a list of the issues that were encountered during the pilot study is identified. Finally, a discussion of proposed future changes is provided to address the issues.

6.1 Research Questions

Two categories of research questions have been presented. Initially, it is asked whether a scaled system can be constructed with a tablet device that allows for the completion and measurement of navigational tasks, based solely on audio feedback. Secondly, four audio displays are proposed and compared using the developed system. These categories are discussed in turn.

6.1.1 Does the System Perform?

The following questions were raised in the previous Research Questions chapter:

- Can a scaled environment be built that provides useful audio feedback for navigational tasks?
- Can subjects navigate in the scaled space and perform tasks satisfactorily?
- Can their performance be appropriately measured?

In Appendix P, Figure P-1 through P-5 provides a graphical summary of the paths taken by the subjects who participated in the pilot study. While not conclusive, a subjective assessment can be made that provides strong evidence that the subjects were completing the navigational tasks satisfactorily using the audio feedback.

During the experiments, measurements were recorded. Subsequent analysis was performed as provided in the preceding chapter. Descriptive and inferential statistics were utilized to show that there are meaningful differences between the audio conditions.

6.1.2 How do the Audio Displays Compare?

Having provided support for the apparatus and measurement methods, specific audio displays are considered. Discussion for both quantitative and qualitative data collected follows.

Initially, consider the analysis of the performance data. Pair-wise comparisons between means were performed using a non-parametric method to answer the hypotheses and sub-hypotheses provided to compare audio displays. Support is found for some of the sub-hypotheses; these are tabulated in Table 5.7. Generally, the hypotheses are supported, with two primary departures: those considering comparisons to the visual feedback condition (A0) and those comparing conditions B1 and B2. A description and explanation is provided for each of these exceptions.

6.1.2.1 Comparisons to condition A0. Condition A0, which offers visual feedback in addition to spatialized audio, was created to provide a baseline for comparisons to the evaluated audio displays. It was anticipated that this could be used as an upper limit on performance, that very effective audio displays would approach these limits. The interpretation of experiment instructions applied by subjects and the actual use of the visual feedback by subjects was not fully anticipated. The investigator observed that different subjects employed different strategies during the visual feedback trials. Some subjects employed a *fastest time* approach, disregarding graphical feedback and accepting higher error rates. Others took a significantly different approach, working at minimizing errors and sacrificing time performance. Based on subject feedback, operation in this mode was also confused by the accompanying spatialized audio. Some subjects expressed that the sound was distracting, others that they simply ignored it. Since subjects employed different strategies and reacted to the accompanying audio in different ways, unplanned variation was introduced that could have been eliminated.

6.1.2.2 Comparisons between conditions B1 and B2. The basis for the comparisons of condition B1 and B2 was the belief that suppressing feedback when the navigator was in a favorable state would reduce cognitive load. With a reduced cognitive load, subjects were expected to navigate better. Unfortunately, the data only support two of the four sub-hypotheses for this question. Therefore, there is only weak support for the research question 3: 'Can the absence of audio feedback be used to improve communication of the relative location of a destination?'

Qualitative data was collect and analyzed to assess user preferences. Support was found for the comparisons of A2 versus A1 and B2 versus B1 (sub-hypotheses H1e and H3e, respectively).

Summarizing, a main effect of audio display group was supported. Pair-wise comparisons showed that many of the expected relationships are supported, and departures exist with time measures and those associated with condition A0. User preferences were consistent with anticipated results. Adjustments for the next phase of this work will be proposed in a later section to address the areas of departure.

6.1.2.2 Single Variate Analysis Issues. In the analysis it was found that the dependent variables which measure accuracy were highly correlated. As such, the standard procedure is to conduct a multivariate analysis to sort out which of the measures might actually be having an effect. This was not done since the purpose of the experiment was to demonstrate how taux could be used to test audio feedback not to develop a set of recommendations for audio feedback. Also, since the dependent measures in question were all a measure of accuracy, the comparisons are accepted as holding no matter what dependent measure contributed to the results.

6.2 General Observations

Several conclusions are made at this point. These are discussed, in turn.

The proposed evaluation system has been developed and shown to allow the construction and evaluation of audio display mechanisms. Comparisons of displays have been undertaken. Using the spatialized audio condition (A1) as a proxy for current systems, it is strongly suggested that making a single iterative improvement (the TalkingGuide, condition A2) results in significant performance improvements. Hopefully, this is just the beginning; continued iterations may yield more significant improvements that dramatically change the state-of-the-art for audio displays for wayfinding.

It is believed that the taux evaluation system, when compared to other research systems, provides more information about subject performance. This added data provides more insight into the relative merits of different display approaches. Several comparisons are offered to support the claim.

When comparing this evaluation system to full scale research systems, it is observed that differences exist in the collection of subject performance data. The number of measures used within taux is generally greater. Ross and Lightman (2005) use time and veer, while Loomis et al. (1998) used time and distance. Taux uses time, distance, planar veer and angular veer. The pilot results suggest that, although some measures are correlated, each measure used collects unique information. Additionally, the frequency and precision of measurement within taux is performed more often and at a higher level of resolution. By way of example, taux periodically measures veer as the minimum distance from the subject's location to the ideal path, while Ross measures the deviation from ideal endpoint for a subject only at the very end of a crosswalk traversal. Comparing these approaches, taux provides higher resolution data in more dimensions and potentially provides more insight into a user's performance.

Considering another research environment, Walker and Lindsay's SWAN virtual environment (2006), similar differences are observed. taux provides more measures of performance, but this time at lower resolution. SWAN/VE provides path efficiency (distance, essentially) and time to completion, while taux provides these measures *plus* angular and planar veer. Again, as in the comparison to full scale research environments, taux paints a fuller picture of the subject performance. The reporting frequency of taux will be re-evaluated for the future planned research.

The third and final general conclusion is that subjects encounter significant difficulty and disorientation if they pass a waypoint without meeting the arrival condition. Once they pass the waypoint, the audio feedback changes dramatically. The specifics of the change vary with the actual display but usually changes in such a way that the subject doesn't process what has happened. Observation of this pattern provides a significant design guideline: that audio display should provide adequate signaling prior to waypoint arrival and should aim to prevent a subject from entering this condition.

6.3 Limitations

The system developed and the subsequent evaluations are subject to certain limitations, specifically: the validity of the apparatus, the methods and the measures. The concerns that arise include external, internal and construct validity and need to be addressed. These are discussed as follows.

6.3.1 External Validity

In the pilot study and proposed follow on research, the subjects used are selected by non-random means. Through observation, it is seen that our subjects may be more affluent, more technologically literate and more spatially adept than the general blind user population. This limitation doesn't discount the research performed, but, does imply that further testing or field trials would be required to present results without this limitation.

6.3.2 Internal Validity

Throughout this research, user performance is measured. Several measures are employed; these introduce possible concerns about their validity. The measures selected are used in similar research, so concerns of validating these measures are minimal. All of the measures are sampled, suffering potential risks associated with the selected sampling frequency. At the most basic level, the timing calculations are dependent upon the scheduling and timing of the hosting personal computer. Additionally, the distances and error measures are collected periodically, and subject to degradation based on the sampling frequency chosen. These timing and sampling errors are expected to be of a negligible size and consequence.

In the case of Walker and Lindsay's System For Wearable Audio Navigation Virtual Environment, a much smaller sampling frequency was use for determining a user's location (2ms vs. 50ms in taux.) Display update frequencies, or response time, were questioned by two subjects. Using a smaller frequency will be evaluated as part of the final test experiment.

6.3.3 Construct Validity

The final area of validity to consider is the mapping of the experiment environment to an in situ application. There are several distinct differences that can be observed between this scaled and full scale environment: (1) scaling of a user's motor movements, (2) a difference in ambient sounds, and (3) the role of environmental cues.

These are each considered more closely. For motor movements, wayfinders use coarser body and leg movements to navigate in the real world, but use finer hand and wrist movements in the scaled environment. Considering taux's measured error, an abrupt sideways motion in the scaled environment may be more costly than the analogous movement would register in a full scale environment. Although this difference exists it is not seen as something that would invalidate this research. In fact, it can be argued that the opposite is true, by scaling the environment and reporting finer errors; an exaggerated effect is observed which provides more contrast for experiments. Work by researchers studying blind navigators (Haber, Haber, Penningroth, Novak and Radgowski, 1993) supports this concern. In this work, the researchers found that locating auditory targets was better served when subjects pointed a body part (nose, head, chest, or finger) rather than rotating a dial. In this work the puck is more analogous to the dial, so it can be argued that accuracy and variability will be adversely affected when compared to real world navigation.

The next difference, the absence of ambient sounds, is immediately obvious. Wayfinders in the full scale environment are required to process ambient noise, and may optionally use environmental audio cues to aid in navigation. These inputs are either very different or completely absent in the scaled environment, raising a concern. Again, as in the scaling discussion above, an argument is offered to support suppression of the full scale effects. In the case of information-less ambient sound, or noise, elimination of variable distractions will aid in the quality of the measurements. In the counter case, this time considering full scale, ambient noise dilutes a subject's attention and degrades performance. This possibility is recognized, but not addressed at present. Consideration has been given to this and is suggested as a topic of future inquiry, where ambient noise is injected into the evaluation system and the effects are better understood through measurement.

The final concern for construct validity is the presence of environmental cues in full scale environments. Since these don't exist in the scaled environment, a subject can't know that they've gone down a stair step, stepped up on a curb or passed through a doorway. In the full scale environment, these cues may aid a traveler in assessing their travel progress. In the end, the presence of environmental cues are expected to make the blind pedestrian's experience better, and may offset some of the positive benefits of a good audio display. For control purposes it is still valuable to compare the audio displays in the absence of environmental cues. Once good audio display methods are identified, these can be adapted and retested in the full scale environment to confirm that environmental cues do not introduce contrary results.

6.4 Issues Encountered

Issues were encountered in many areas during this research. These were handled as they were encountered, and were handled previously in the relevant areas within this thesis. Issues in two additional areas are related to learning and route geometry. These are of a more global nature and are discussed here.

6.4.1 Learning

In the experiment procedure for the pilot study, care was taken to confirm that a subject had performed enough practice within a particular condition before proceeding with the actual trials. The TimePerUnitDistPerWP measure was examined to assess whether the subject had trained to criteria, by looking for a plateau effect. This value was examined on a per-waypoint basis. During the pilot study, plateau effects were not observed, and a subjective criterion was substituted by the investigator. The investigator looked for general proficiency or evidence that the subject was listening to the feedback and making appropriate decisions.

After the experiments were conducted, further inquiry was done. It was observed that both time and distance measures offer limited value for 'training to criteria' analysis. In the case of the taux tool, both of these measures are normalized to account for differences in different trials. Contrary to initial intuition, these are awkward to use for criteria comparisons since their normalized values are ambiguous prior to trial completion. Based on this observation, it was identified that error measures may provide better data for training criteria. In order to study this, post hoc, trend information for off target error and heading error were plotted for each condition by subject (see plots in Figure Q-1 through Figure Q-5). Considering the plots for A1, A2, B1 and B2, it is observed that no downward trend is observed for off target error and that a downward trend exists in the heading error performance for the conditions B1 and B2. From these observations, it is suggested that heading error may be the best measure for learning. Heading error will be monitored in future studies as a potential indicator of learning.

6.4.2 Route Geometry

In pilot study planning, it was noticed that certain configurations of route data presented difficulty for subjects. Paths that pointed toward the sides of the tablet or that had several turns that oriented the path to point back toward the subject were difficult to follow. Subjects became disoriented when their egocentric coordinate system became inconsistent with that of the puck. Different subjects adjusted in different ways. Some would stand and attempt to circle the tablet and the table it was on; others would tip their head abruptly. Still others did nothing and struggled. Since this appeared to introduce variation based on a particular subject's strategy, the routes were modified to follow a constrained pattern. All paths originate from the bottom area of the tablet and terminate near the top of the tablet. Routes are not permitted to turn such that they tend toward the sides or back toward the bottom of the tablet. Additionally, routes are constrained to turn no more than 135 degrees at each waypoint. This approach introduces a limitation in the paths that can be used eliminating subject confusion and variability.

6.5 Proposed Improvements

As a result of building the initial implementation and running the pilot study described within the proposal, the following improvements were identified. These were divided into two categories, near term and long term. The near term items were planned for implementation during the successive research work resulting in this dissertation, while the longer term items were identified and deferred to a future date.

6.5.1 Near Term

- Modify the visual feedback condition (A0) to use paper templates on the tablet. A template will be created for each trial, with the corresponding route clearly printed on it. The graphical feedback from the investigator's console will no longer be used by the subject for visual feedback. Additionally, the accompanying spatialized audio feedback will no longer be displayed during this condition. The instructions will be modified to give the subject clearer instructions about navigating the path with a consideration of both speed *and* accuracy.
- Change normalization for time measurement. Rather than using time/unit of ideal distance, time/unit of ideal distance/waypoint will be used.
- Heading error will be monitored during practice sessions for evidence of learning.
- Frequency of speech used in spatialized audio conditions (A1 and A2) will match the frequency of tonal reports used in varying pitch conditions (B1 and B2).
- Varying pitch displays (B1 and B2) will be improved to provide left and right signaling in addition to the current varying pitch signals.
- The experimental method will be modified to be counterbalanced, allowing identification (or rejection) of ordering effects.
- Increase the sampling resolution for location reports.
- Reduce the arrival radius to one half of the current value.
- Exclude all subjects with hearing impairments.

6.5.2 Long Term

- Take results to full scale environment (indoor or outdoor wayfinding system) and validate.
- Work with psychoacoustic domain experts, perform more display iterations, implement and evaluate more display types
- Enhanced varying pitch mode to report based on movement, not time
- Investigate the effects of varying the scaling between the virtual space on the tablet and the 3D audio virtual space
- Incorporate hand held or other portable devices (example cell phone)

- Provide introspection capabilities in taux to permit inspection of new display components for easy display and manipulation in the investigator's console
- create the proper transformation to move the puck's datum from its centroid to its central forward extent (its nose, essentially)
- add simulated ambient sound
- look at making the hints spatialized
- evaluate the effects of fatigue
- evaluate the effect of low quality speech v. high quality speech in navigating
- substitute new 3D sound models
- tighter integration with CAD system
- Plot heading error and off target error for each trial
- Provide signaling that the subject has traveled past a waypoint without being near enough to it to register an arrival

CHAPTER 7

FINAL TEST EXPERIMENT

The focus of this dissertation is on the taux system. Since taux is to be used to support the running of experiments that evaluate audio feedback for navigation, its usage is peculiarly entwined with the experiments that it supports. The initial test experiment had problems not only in the selection and application of stimulus to test but also in the operation of taux and the design of the initial test experiment. Thus, although the normal intent of a subsequent set of experiments using taux is that of iteratively testing the audio feedback stimulus, the subsequent experiment in this thesis (a) improves the experiment design and (b) improves taux in addition to adjusting the audio feedback.

Since the experiment procedures do not differ from that of the test experiment, the experiment proecedure and design are not described in detail except where these factors differ from the test experiment. Overall, this chapter will present the following. First, a summary of the changes that were made to the evaluation system and to the research method is provided. Next, the results of the final experiment are presented as graphical plots of the subjects' navigation paths. Both descriptive and inferential statistics are provided for the measures taken off the navigation paths in addition to subjects' attitudes towards each audio display. These were collected through a post-experiment questionnaire. This chapter's focus is on the analysis of the data collected in this second study which corrects a series of flaws found in the first study. A discussion of these results will follow in the next chapter. This discussion will note that new issues with taux and with the experiment design were found that require more experiments to correct these flaws before being able to effectively test the effect of the different forms of audio feedback

7.1 Revisions From Pilot

As described in Chapter 6, multiple changes were identified after running the test experiment. These were divided into two categories: near term and long term. Near term changes were anticipated to be completed prior to running the final experiment. Long term changes are under consideration for implementation after completion of the final experiment. The near term changes have been performed, with two deviations. This will be discussed in a moment. The following changes were made completely in accordance with what was anticipated:

- Modify the visual feedback condition (A0) to use paper templates on the tablet. A template was created for each trial, with the corresponding waypoints clearly marked on it. The graphical feedback from the investigator's console was no longer be used by the subject for visual feedback. Additionally, the accompanying spatialized audio feedback is no longer displayed during this condition although subjects are told when a waypoint has been reached. The instructions have been modified to give the subject clearer direction about following the template for both speed *and* accuracy.

- Change normalization for time measurement. Rather than using time/unit of ideal distance, time/unit of ideal distance/waypoint is used.

- Frequency of speech used in spatialized audio conditions (A1 and A2) will match the frequency of tonal reports used in varying pitch conditions (B1 and B2).

- Varying pitch displays (B1 and B2) will be improved to provide left and right signaling in addition to the current varying pitch signals.

- The experiment method will be modified to be counterbalanced, allowing control for possible order effects. A Latin Squares design was utilized and is presented in Table 7.1.

- Increase the sampling resolution for location reports. The sampling interval was changed from 50 milliseconds to 20 milliseconds.

- Reduce the arrival radius to one half its current value. The value was changed from 750 tablet units to 375 tablet units. Three hundred seventy five tablet units equals 0.148 inches, or just slightly more than 1/8 of an inch.

- Exclude all subjects with hearing impairments

Table 7.1 Ordering Utilized for Latin Squares Design

	Condition				
Subject#1	A1	A2	A0	B1	B2
Subject#2	A2	B1	A1	B2	A0
Subject#3	B1	B2	A2	A0	A1
Subject#4	B2	A0	B1	A1	A2
Subject#5	A0	A1	B2	A2	B1
Subject#6	B2	B1	A0	A2	A1
Subject#7	A0	B2	A1	B1	A2
Subject#8	A1	A0	A2	B2	B1
Subject#9	A2	A1	B1	A0	B2
Subject#10	B1	A2	B2	A1	A0

Due to scheduling issues, time permitted inclusion of all of the near term changes prior to the proposal defense. Additionally, during this interval and once the changes were made, five sighted (but not blindfolded) subjects were run. It was anticipated that these subjects would be part of the final experiment. Subsequently, it was determined that the final experiment would utilize only *blindfolded* sighted subjects, and thus not allowing the combination of the data collected from these five subjects with the remaining data.. The five subject runs were not without value; these trials performed a rigorous walk-thru of the evaluation system after it had undergone multiple changes. One serious software bug, arising as a side effect of the timing changes identified previously, was identified and remedied before the final group of ten subjects was run.

As noted above, two deviations from the prescribed ‘near term’ list were taken. It was planned to monitor heading error as training criteria during practice sessions to determine a subject’s achievement of a threshold learning level. While running the five sighted subjects, this data was collected and monitored. It was determined that this data was no better at indicating asymptotic learning performance than the previously monitored measure of off target error. As a result, monitoring of learning data was discontinued for the final ten subjects. Subjects were given a set number of practice trials in the experiment but learning was not measured. This is left as a topic for future research.

The second deviation was different. In this deviation, two 'long term' modification items' timelines were accelerated allowing them to be included in the near term schedule. First, while modifying the visual feedback condition, it was recognized that allowing the puck's pivot point to remain at the puck's geometric center would probably result in confusion for the subject. By locating this rotation point at the forward central extent of the puck, subjects would complete this condition more naturally. In order to maintain similarity amongst conditions, the pivot point was relocated for ALL conditions. Second, it was determined that the varying pitch conditions (B1 and B2) could be modified to not only include the left/right signaling but also to report audio updates whenever the subject's motion warranted a note change. So, in addition to reporting a pitched note on a one second intervals, more frequent updates were provided to instantly signal direction changes.

7.2 Data Collected and Analysis of Data

In accordance with the procedures outlined in Chapter 4 and the instruments described in Appendices A-K, ten blindfolded subjects were run. All subjects have good vision either with or without correction. Subject demographics were collected and are as follows. Subjects were asked questions about their age, gender, education level, computer proficiency and hearing ability. The follow paragraph summarizes their responses.

Of these ten participants, four were female and six were male. Two reported left handedness, while eight reported right handedness. None reported that they were ambidextrousness. Two subjects had a high school level education, one had a bachelor's degree and the seven remaining subjects reported an advanced level of education beyond a three- to four-year college education. The average age was 44.1 years. The subjects reported computer use of 2-10 hours per day, with an average of 5.85 hours per day. Participants reported computer experience ranging from 10 to 40 years, with a mean value of 19.4 years. Allowing for corrected vision, four subjects exhibited 20/20 vision while two exhibited 20/30. Of the remaining four subjects, visual acuity was measured at one each of 20/13, 20/15, 20/25 and 20/70.

7.2.1 Subjects Path Data

As previously illustrated in Figure 5.1 and Figure 5.2, a subject's traversal can be graphically plotted for comparison with the scheduled path. The following figures (Figure 7.1 and Figure 7.2) show traversals for two subjects in two conditions in two trials. The data for all subjects in all conditions can be viewed in the five plots found in Appendix R.

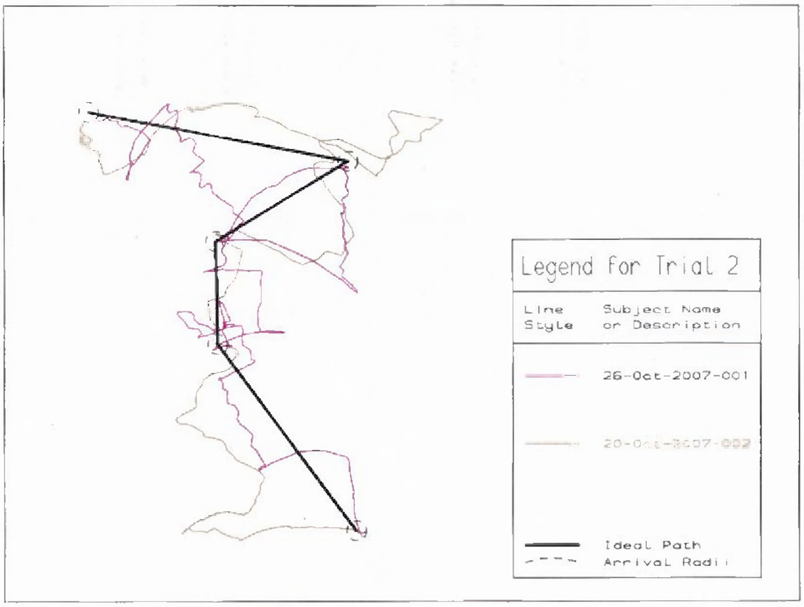


Figure 7.1 Traversals of two subjects in trial 2 of condition A1.

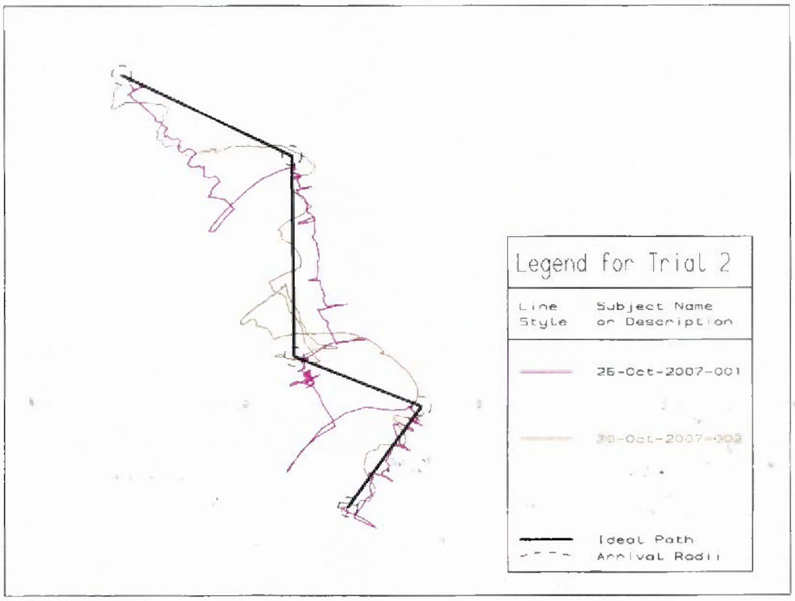


Figure 7.2 Traversals of two subjects in trial 2 of condition A2.

It can be seen from the data displayed in Figure 7.1 and Figure 7.2 that the subjects appear to converge upon the targeted waypoint better in condition A2 than in condition A1. Several other observations are possible. In both conditions, the subjects missed a waypoint. A severe performance penalty, in the form of excess distance traveled, can be seen for this navigation error. Additionally, several wide sweeping arcs are present. These typically appear when a subject rotates the puck in order identify the direction of a destination. When the puck is not rotated about its pivotal center point, these arcs exaggerate the apparently intended rotational motion.

Several adjustments to the data collected were necessary. For three subjects, they were not able to complete navigation in a particular condition. The affected condition was 'spatial audio' (without hints, labeled as condition "A0"). In one of the cases the subject was able to complete one of three trials before giving up or asking for help; this data is included in the analysis. In the other two cases, both subjects did not make it past the practice sessions and no data was recorded. These omissions are easily identified by looking at the tracking plots in Appendix R and observing which subjects are missing an entry in the plot's legend.

Some data was removed or edited from the analysis. There were two conditions that warranted this handling. In the first case, when a subject requested help during a trial, that set of observations for that entire trial was removed from the dataset. This occurred five times: in condition B1 for subject 20-Oct-2007-001 (route 1.dat), condition B1 for subject 17-Oct-2007-001 (routes 1.dat and 2.dat), condition A1 for subject 19-Oct-2007-001 (route 3.dat) and condition A1 for 29-Oct-2007-001 (route 2.dat). This problem highlights a shortcoming in the experiment design (ceiling effect) and an area of further inquiry which is included in the future research section. Under the second scenario, changes to the puck's pivot point provoked an "out of bounds" message for some users who were completing navigation to the final point in the route (This was condition A2, route dataset 3.dat). This problem arose as a side effect of the repositioning of the puck's pivot point and only affected some of the subjects. In this case, rather than invalidating the entire route's data for all the subjects, the data was amended to truncate the route to only contain the points from the first point until the next to the last point. This effectively severs that last waypoint's data and measurements from the trial. All dependent measures were adjusted accordingly. For example, the DistRatio measure was calculated based on the new, shorter scheduled distance and not the original scheduled distance.

7.2.2 Descriptive Statistics for Performance Data

After the described maintenance of the collected data was performed, the mean, minimum, maximum and standard deviation were calculated. The descriptive statistics for the dependent variables are summarized in Table 7.2. Source code for the statistical package R that was used in these calculations can be found in Appendix N.

Table 7.2 Descriptive Statistics for Final Experiment

Group	Table of Means					
Spatialized Audio (A1)	**Variable**	**N**	**Mean**	**Std. Dev.**	**Min**	**Max**
	DistRatio	21	2.258	0.804	1.416	4.319
	AvgOTE	21	1106.2	353.73	630.50	2000.0
	AvgHE	21	0.831	0.369	0.322	1.645
	T/UD/WP	21	0.672	0.294	0.315	1.464
Spatialized Audio + Hints (A2)	**Variable**	**N**	**Mean**	**Std. Dev.**	**Min**	**Max**
	DistRatio	30	1.738	0.460	1.208	2.897
	AvgOTE	30	694.10	181.29	337.63	1136.10
	AvgHE	30	0.432	0.230	0.163	1.319
	T/UD/WP	30	0.835	0.374	0.377	2.200
Spatialized Audio + Visual Feedback (A0)	**Variable**	**N**	**Mean**	**Std. Dev.**	**Min**	**Max**
	DistRatio	30	1.640	0.318	1.206	2.657
	AvgOTE	30	511.15	160.69	272.12	866.86
	AvgHE	30	0.953	0.285	0.458	1.617
	T/UD/WP	30	0.150	0.056	0.056	0.253
Varying Pitch (B1)	**Variable**	**N**	**Mean**	**Std. Dev.**	**Min**	**Max**
	DistRatio	27	2.097	1.060	1.270	6.302
	AvgOTE	27	952.90	589.57	458.15	3428.2
	AvgHE	27	0.515	0.260	0.173	1.111
	T/UD/WP	27	0.695	0.387	0.218	2.003
Varying Pitch w/Silence (B2)	**Variable**	**N**	**Mean**	**Std. Dev.**	**Min**	**Max**
	DistRatio	30	2.083	0.547	1.461	3.939
	AvgOTE	30	793.03	203.47	461.62	1268.6
	AvgHE	30	0.428	0.134	0.187	0.683
	T/UD/WP	30	0.795	0.410	0.294	1.984

As done in Chapter 5, the group means are plotted along with other descriptive statistics for visual comparison. Please refer back to Table 5.2 for a full display of the descriptive statistics. The plots reflecting the descriptive statistics reported in Table 7.2 can be viewed in Figure 7.3.

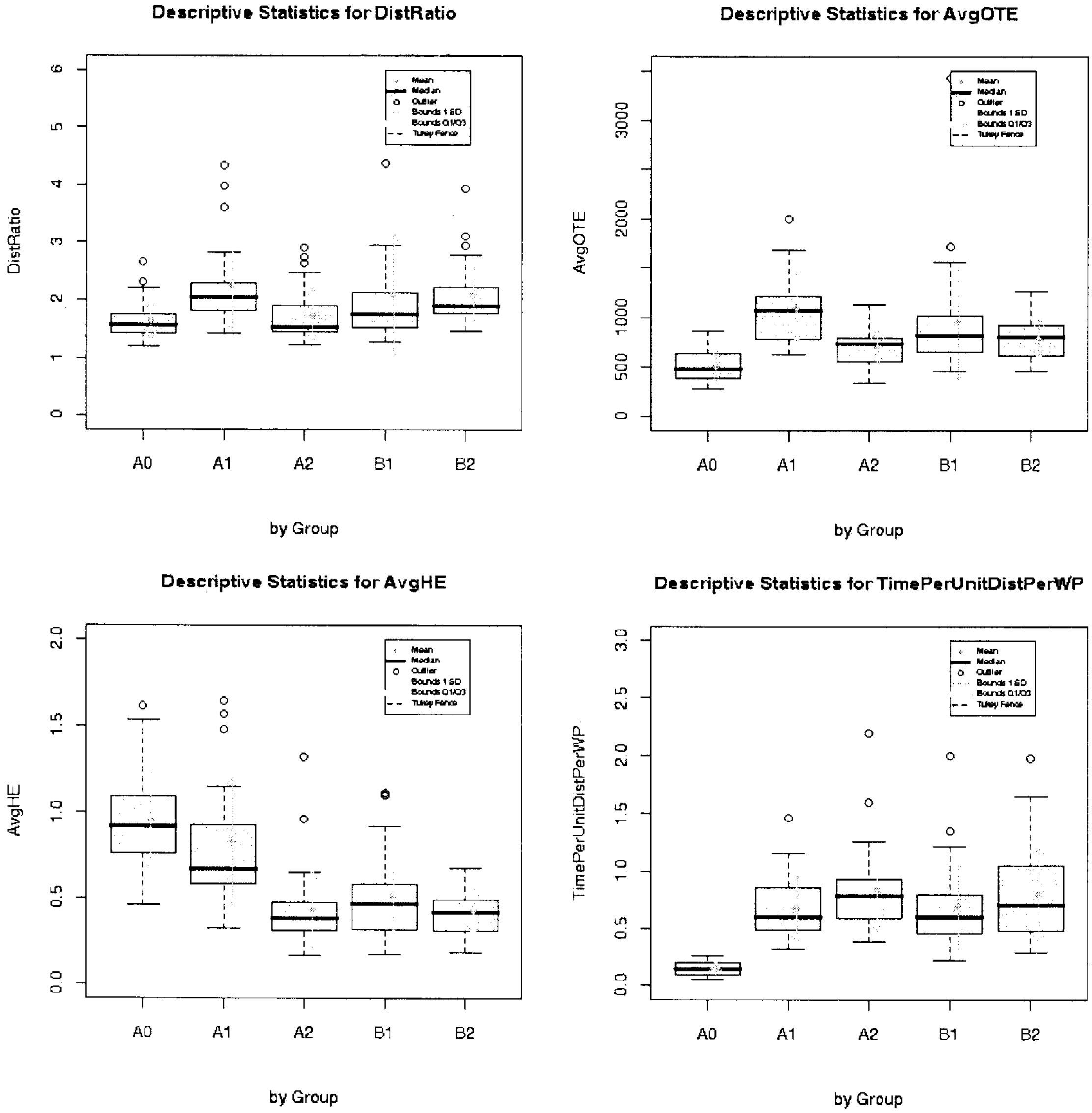


Figure 7.3 Summary plots for descriptive statistics of dependent variables.

7.2.3 Inferential Statistics for Performance Data

Following the same steps as those in Chapter 5, an analysis is performed to identify the amount of correlation between dependent variables. The results are displayed in Table 7.3

Table 7.3 Pearson Product-Moment Correlation Coefficients Between Dependent Variables for Final Experiment

Note: Significant Values in Boldface

Dependent Variable	DistRatio	AvgOTE	AvgHE	TimePerUnitDistPerWP
DistRatio	1.00	**0.69**	**0.24**	**0.41**
AvgOTE	**0.69**	1.00	**0.19**	**0.21**
AvgHE	**0.24**	**0.19**	1.00	**-0.47**
TimePerUnitDistPerWP	**0.41**	**0.21**	**-0.47**	1.00

Consulting a table of critical values for r, any value over 0.167 is considered significant ($r_{\alpha=0.05,n=138}=0.167$). Significant values are identified in Table 7.3 in boldface type. It is observed that correlations above 0.4 exist for three pairs of dependent measures: DistRatio with AvgOTE and TimePerUnitDistPerWP and AvgHE with TimePerUnitDistPerWP. This suggests that a multivariate analysis needs to be considered in comparing audio conditions.

To further assess whether a multivariate analysis is appropriate, assumptions are checked to determine normality. The Shapiro-Wilk statistic is calculated for each sample of the dependent variable within each condition. The associated probabilities are tabulated in Table 7.4. It is seen by the low values of p that many samples do not exhibit normality and thus, a multivariate analysis of variance cannot be used. Since the normality assumption is not satisfied further analysis to determine homogeneity of variance is not conducted. This suggests a variety of approaches for comparing conditions. First, corrections can be applied to the distributions to make them normal. It can be seen from the boxplots that the distributions of each variable are skewed on the high end. This is because of the difficulties the subjects have when they reach a waypoint. Either a threshold can be set around the waypoint and the data from this part of the path ignored or the distribution can be made normal and homogeneous through a logarithmic transformation. Then a multivariate analysis of variance and paired comparisons can be carried out. Alternatively, new techniques exist for non-parametric multivariate analyses but these will have a low power. A decision was made to take a third approach, that is, to ignore the requirement for a multivariate analysis and run a simple non-parametric test comparing the conditions of interest. This was done primarily because the hypotheses used in this study were not to build a theoretical basis for guiding audio wayfinding design but as examples of how such a type of study could be done using taux. As such, the results from the study are suspect, but illustrative of what could be done if one wanted to use taux to build up a theory of audio wayfinding.

Table 7.4 Summary of Probabilities, Tabulated by Condition and Dependent Variable, for Shapiro-Wilk Statistic

	A0	A1	A2	B1	B2
DistRatio	0.001	0.002	0.001	<0.0001	0.001
AvgOTE	0.165	0.121	0.568	<0.0001	0.625
AvgHE	0.368	0.023	<0.0001	0.022	0.257
Time/UD/WP	0.476	0.339	<0.0001	0.003	0.234

The Mann Whitney statistic (U) and associated probabilities was calculated to draw inference about the differences observed between the group means for the A0 through B2 conditions. This distribution-free approach allows substitution of order statistics for the collected data to support the study's hypotheses. Table 7.5 provides a summary of the U statistic and associated probabilities for a one-tailed two sample approach. The R source code for this analysis in included in Appendix N. It can be seen that fifty percent of the hypotheses are supported; the departures will be discussed in the next chapter.

Table 7.5 Paired Comparisons Using Mann Whitney Statistic. Values Displayed are U Statistic and Corresponding Probability (p), with Significant Values Shown in Bold at 95% Level.

	A2 v. A1	B2 v. B1	A0 v. A1	A0 v. A2
DistRatio	**464** **0.002**	321 0.910	**500** **0.0001**	485 0.306
AvgOTE	**535** **<0.0001**	435 0.320	**607** **<0.0001**	**696** **<0.001**
AvgHE	**554** **<0.0001**	463 0.180	222 0.963	63 1.000
Time/UD/WP	219 0.968	342 0.843	**630** **<0.0001**	**900** **<0.0001**

Supported/unsupported status is identified for each of the experiment hypotheses in Table 7.6.

Table 7.6 Supported/Unsupported Status for Performance Hypotheses During the Final Experiment

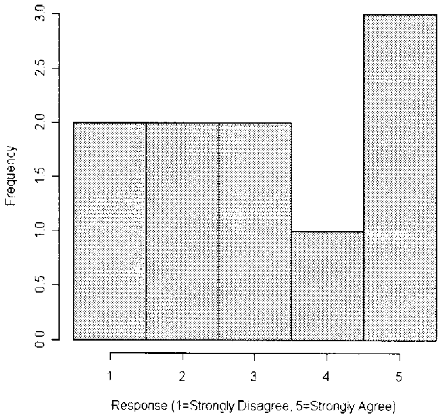
Hyp.	Status	Description
H1		Subjects perform better with the Talking Guide (A2) than with Spatialized Audio (A1).
H1a	Not Supported.	A2 completion time will be lower that A1 completion time.
H1b	**Support**	**A2 distance efficiency will be lower that A1 distance efficiency.**
H1c	**Support**	**A2 off target error will be lower that A1 off target error.**
H1d	**Support**	**A2 heading error will be lower than A1 heading error.**
H2.		Subjects perform better with Visual Feedback (A0) than with A1 or A2. (H2a – H2d considers A0 v. A1.)
H2a	**Support**	**A0 completion time will be lower than A1 completion time.**
H2b	**Support**	**A0 distance efficiency will be lower that A1 distance efficiency.**
H2c	**Support**	**A0 off target error will be lower than A1 off target error.**
H2d	Not Supported	A0 heading error will be lower than A1 heading error.
H2		Subjects perform better with Visual Feedback (A0) than with A1 or A2. (H2e – H2h considers A0 v. A2.)
H2e	**Support**	**A0 completion time will be lower than A2 completion time.**
H2f	Not Supported	A0 distance efficiency will be lower than A2 distance efficiency.
H2g	**Support**	**A0 off target error will be lower that A2 off target error.**
H2h	Not Supported	A0 heading error will be lower that A2 heading error.
H3		Will Pitch w/Silence for on-course (B2) be better that pitch alone (B1)?
H3a	Not Supported	B2 completion time will be lower than B1 compction time.
H3b	Not Supported	B2 distance efficiency will be lower than B1 distance efficiency.
H3c	Not Supported	B2 off target error will be lower than B1 off target error..
H3d	Not Supported	B2 heading error will be lower than B1 heading error.

The hypotheses results presented here will be discussed further in the next chapter.

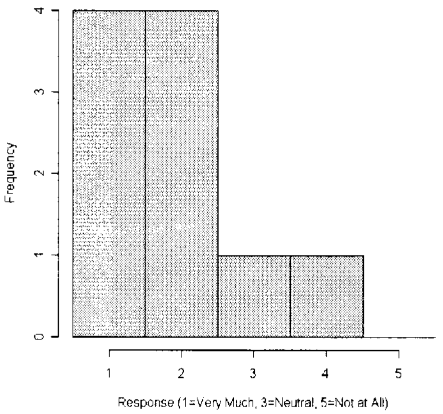
7.3 Subject Survey Results

In addition to the performance data collected for each subject, an exit questionnaire was administered to capture their attitudes and beliefs about the navigational feedback methods. The questionnaire was administered as it had been in the pilot, without substantive modification. A minor error was corrected to remove a duplicate question, resulting in a question numbering change from the previous pilot phase. The questionnaire is provided in Appendix I. The following bar plots (Figure 7.4) summarize the responses that were provided.

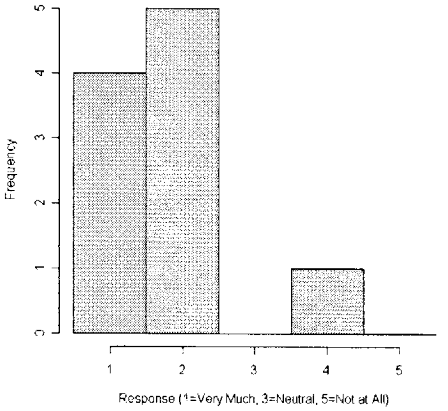
Question 1: I preferred hearing a sound at the location versus the varying pitch sounds



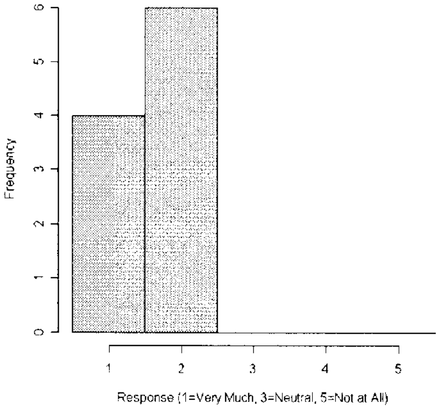
Question 2: If I were lost in the woods, and all I had was a headset speaking "Location, location, ..." to guide me, it would help me



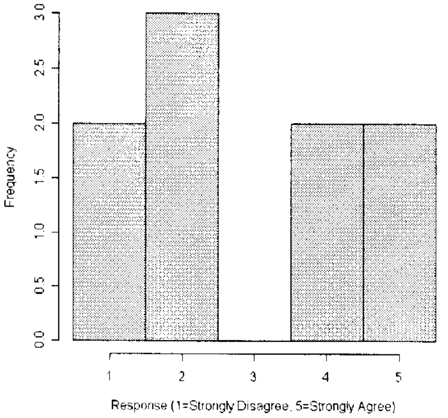
Question 3: If I were lost in the city and became disoriented, and all I had was a headset that played the voice speaking "Location, location, ..." to guide me, it would help me ....



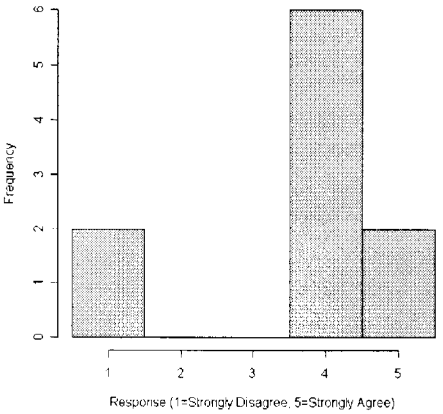
Question 4: If I were lost in the woods, and all I had was a headset that played vaying pitch sounds to guide me, it would help me ....



Question 5: When listening to varying sounds, I preferred silence to a high pitch when I was facing directly at the location



Question 6: I feel that either of the demonstrated methods (varying pitch tone or sound at the location) could allow me to find my destination in the real world.



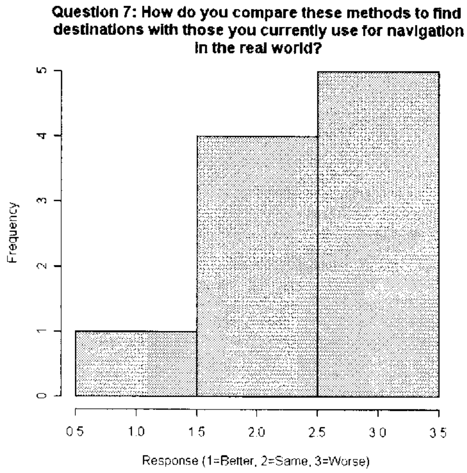


Figure 7.4 Subject responses about preferences for final experiment.

Table 7.7 summarizes both the descriptive and inferential statistics for this same data. For survey questions one through six, the sample mean is provided. This value is compared in a one-sample test by comparison against the neutral response (a neutral response is equal to three, in both Type A or Type B scales. The Type A/TypeB scales used for each question and descriptions of each type are also listed in Table 7.7). The null hypothesis is tested to determine if the sampled mean is equal to a neutral response, and rejected if the neutral response value falls outside the 95% confidence interval of the mean value for the data collected. In question seven, a similar approach is employed. Since question 7 utilizes only three possible responses, the one-sample test is applied by comparing the mean of responses with the middle state ('same', where the value is equal to two).

Table 7.7 Descriptive and Inferential Statistics for Attitudes and Beliefs Data Collected

Q#	Question	Score Type	Average Score	t statistic	*p*
1	I preferred hearing a sound at the location versus the varying pitch sounds	A	3.1	0.20	0.85
2	If I were lost in the woods, and all I had was a headset speaking "Location, location, ..." to guide me, it would help me	B	1.9	-3.50	<0.01*
3	If I were lost in the city and became disoriented, and all I had was a headset that played the voice speaking "Location, location, ..", to guide me, it would help me	B	1.8	-4.13	<0.01*
4	If I were lost in the woods, and all I had was a headset that played varying pitch sounds to guide me, it would help me	B	1.6	-8.57	<0.01*
5	When listening to varying sounds, I preferred silence to a high pitch when I was facing directly at the location	A	2.9	-0.206	0.84
6	I feel that either of the demonstrated methods (varying pitch tone or sound at the location) could allow me to find my destination in the real world.	A	3.6	1.327	0.22
7	How do you compare these methods to find destinations with you currently use for navigation in the real world?	C	2.4	1.81	0.10
Note:	* items significant at the 95% level				

Score Type defined by:

A	1=Strongly Disagree, 2=Disagree, 3=Neutral, 4=Agree, 5=Strongly Agree
B	1=Very Much, 2=Somewhat, 3=Neutral, 4=Not Much, 5=Not at All
C	1=Better, 2=Same, 3=Worse

When asked about preferred displays (Question 8), subjects ranked them in this order:

Table 7.8 Comparison of Means of User Preferences for Display Modes in Final Experiment

Condition	Description	Rank Sum	Score (Mean Rank)
A2	Spatialized audio with Hints	17	2.111
A1	Spatialized Audio	21	2.444
B1	Varying Pitch	22	2.555
B2	Varying Pitch with Silence	20	2.889

The means provided suggest that subjects prefer B1 to B2, and also prefer A2 to A1. The preference of A2 to A1 was originally hypothesized; the preference of B1 to B2 is counter to the experiment's hypothesis. It should be noted however, that these comparisons are not statistically significant, in part because this is subjective data and a N of 10 is too small for this type of evaluation. The method used to analyze significance for rank ordered selections (without ties) is taken from Quandt (http://www.liquidasset.com/corsica.htm). An archival of the method's description can be found in Appendix S. An alpha level of 0.05 was used. The following hypotheses for the post-interview measures are re-visited to determine if user preferences are consistent with the hypothesized predictions.

Table 7.9 Hypotheses and Supported/Unsupported Status for User Preferences

Hyp.	Status	Description
H1e.	Support*	Subjects will prefer Talking Guide (Spatialized Audio with hints, A2) to Spatialized Audio (A1).
H3e.	Not Supported*	Subjects will prefer Pitch w/Silence (B2) to Varying Pitch (B1).

* not statistically significant

CHAPTER 8

DISCUSSION OF RESULTS FROM FINAL TEST EXPERIMENT

Although detailed experiments are run throughout this thesis, the focus of the dissertation is not on the results from these experiments per se, but rather on the efficacy and viability of running the experiments using taux. Thus the results from the experiments are important in that they show that taux can be used to conduct research that tests the design of audio feedback. This chapter therefore provides a discussion of the results presented in Chapter 7 with the intent of illustrating that iterative studies can be run to understand how humans respond to audio feedback navigation. It uses these results to then discuss a greater whole, that of evaluating how well taux works. Both the discussion of the final experiment and of the larger experiment evaluating taux are presented in this chapter.

8.1 Discussion of Results

As was done in the test experiment (Chapter 6), this chapter will consider both the original research questions and the research questions posed for the final test experiment that was presented in the preceding chapter. Where possible, evidence to support the key research questions of the thesis is provided.

8.2 Research Questions

Two categories of research questions have been presented. Initially, a set of questions are asked as to whether a scaled system such as taux can be constructed with a tablet device that allows researchers to run experiments that examine different forms of audio feedback for guiding navigation,. Secondly, a set research questions are asked about the actual experiments that test five proposed audio displays that are designed and compared using the developed system. Each of these categories is discussed in the subsequent sections beginning with the research questions related to taux.

8.2.1 Does the System Perform?

The following questions were raised in the previous Research Questions chapter:

- Can a scaled environment be built that provides useful audio feedback for navigational tasks?
- Can subjects navigate in the scaled space and perform tasks satisfactorily?
- Can their performance be appropriately measured?

The first question is again answered through observation, where the implemented system was successfully utilized to conduct an experiment. To address the second question, the reader is directed to Appendix R for the Final Experiment Tracking Plots (Figure R-1 through R-5) which graphically summarize the paths taken by the subjects who participated in the final study. While not conclusive, and as in the pilot, a subjective assessment can be made that provides evidence that the subjects were completing the navigational tasks, satisfactorily, based on the audio feedback. And, as in the pilot, a generalization can not be performed that relates this scaled navigation to real world navigation based on the same arguments suggested earlier.

The third question considers appropriate measurement of the subjects' navigational performance. During the experiments, several performance measurements were recorded. Subsequent analysis was performed as provided in the preceding chapter. An overall multivariate test was contemplated, but the collected data did not meet the necessary normality requirement for this multivariate test. As a result, a dimension-free analysis was performed doing paired comparisons of the related dependent measures.

8.2.2 How do the Audio Displays Compare?

Having provided support for the apparatus and measurement methods, specific audio displays are considered. Discussion for both performance and the subject preference data collected follows.

Initially, consider the performance feedback. A non-parametric pair-wise comparison of means was performed to answer the hypotheses and sub-hypotheses provided to compare audio displays. Support is found for some of the sub-hypotheses; these are tabulated in Table 7.6. Half the hypotheses are supported as anticipated, with four primary departures: (1) comparisons of all performance measures between B2 and B1, (2) comparisons of AvgHE from any condition to the A0 condition, (3) DistRatio comparison between A2 and A0 and lastly (4) time measurement (TimePerUnitDistPerWP) between A2 and A0. A description and explanation is provided for each of these exceptions.

8.2.3 Comparisons of all performance measures between B2 and B1.

In the pilot study, it was found that subjects did not perform better in condition B2 when compared to B1.The final test experiment produced similar data with a similar conclusion. It was anticipated that removing sound and replacing it with silence for an on target condition would yield better performance, but the results do not support this hypothesis.. Additionally, several users expressed dissatisfaction with B2's mechanism during the final study. This result will be discussed futher in the next section.

8.2.4 Comparisons of AvgHE from any condition to the A0 condition.

AvgHE is calculated by sampling instantaneous heading error during a trial and computing the average of all observations. By observing TimePerUnitDistPerWP for A0 and comparing it to all other conditions, it is seen that the completion time is significantly smaller for A0. Since AvgHE is sampled and averaged, the values at waypoint transitions (which are significantly larger than those encountered during waypoint to waypoint navigation) have a larger effect on the average than they do in conditions where subjects spend more time in between waypoints. This possible explanation suggests that AvgHE may not be the best measure for angular heading errors and that future work is needed to determine how to improve this measure.

8.2.5 DistRatio comparison between A2 and A0.

This exception comes as a bit of a surprise, and is well received. It was anticipated that sighted users would be able to more accurately navigate with visual feedback than with the rendered sounds. More specifically, the accuracy measures (AvgHE, AvgOTE and DistRatio) should be lower for the visual feedback condition. AvgHE didn't show this, a possible explanation is offered in the preceding paragraph. AvgOTE does show this difference as anticipated. DistRatio is a bit of a surprise, however. The failure of this hypothesis and observation of the data suggest that subjects are covering roughly the same distance with visual feedback (A0) and with assisted, spatial audio (A2). Possible explanations are that the navigation is as efficient with sound as with visual feedback, or, alternatively and more likely, that the experiment (and taux) are not capturing the right data about the visual navigation. This is discussed in more detail in the discussion of the experiment limitations.

8.2.6 Time measurement (TimePerUnitDistPerWP) between A1 and A2.

It was anticipated that subjects would navigate more quickly with hints (A2) than without (A1). The performance data collected is counter to this intuition. A possible explanation comes from examination of the performance data's descriptive statistics. It is seen that subjects perform better with A2 versus A1 when considering AvgHE, AvgOTE and DistRatio. Considering that these are all measures of accuracy, it is suggested that a tradeoff in time exists to achieve these higher levels of accuracy.

User data was collect and analyzed to assess user preferences. Support was found for the comparisons of A2 versus A1 but not for B2 versus B1 (sub-hypotheses H1e and H3e, respectively). Considering B2 versus B1 more closely, this result is counter to the result found in the pilot study. The results found are not statistically significant; it is anticipated that running studies with larger samples could yield statistics with significant results. The differences in B2 v. B1 between the pilot study could be a result of statistical insignificance, or, alternatively, because of the changes introduced for the final study where audio feedback for heading error is coded for both magnitude and direction through left/right signaling.

8.3 Problems with the Final Test Experiment

The final test experiment was constructed to address issues encountered while running the earlier test experiment. The results of that earlier work showed that improvements needed to be made in three areas: the basic functioning of the system, the design of the experiment and the research methods. As was done with the earlier experiment, a retrospective analysis is performed to identify weaknesses of the latest approach and to suggest future improvements that would mitigate these shortcomings. The following paragraphs will revisit these three areas, in turn.

8.3.1 Basic System Function

Several changes were made to the basic system prior to running the final experiment. These include: a decrease in the capture radius used, an increase in the sampling resolution utilized and an adjustment of the periodic rate at which repetitive audio signals were produced (making them more consistent between conditions).

In addition to the basic improvements mentioned, one display capability was improved. In the cases of varying pitch output (conditions B1 and B2), the feedback was altered to signal not only the magnitude of the error but also the direction of heading error by displaying it exclusively on the subject's left or right side.

In order to demonstrate the iterative capability of taux, it would have been ideal to examine the benefit of the improvement where left/right signaling was added by comparing it to the prior B1 condition. But, given the number and degree of the basic system changes, it was determined that too many things had changed and it would not be a useful comparison. For example, B1 performance for the final test experiment (B1') could not be compared with B1 performance from the earlier experiment because so many things had changed in taux that might have caused a difference between B1' and B1

It was originally intended to demonstrate the value of iterating from one experiment to the next, while making incremental improvements to the feedback. But, as things evolved, it was seen that the final test experiment was really needed to be another test experiment, or validation of the system, to address the taux problems identified in the test experiment. It is observed that further iteration is required to begin to analyze differences between an earlier display and a suggested improved display after making incremental improvements.

The reasoning made to abandon comparisons from the early experiment to the final experiment and focusing on system validation is supported by what happened during the operation of the final test experiment. It was found that after the basic functions were updated three of the initial subjects for the final experiment exercised the system in such a way that caused it to hang. A serious software defect was found that caused this condition to arise. The software was repaired and the data from these subjects was removed from the analysis.(It also turns out that these subjects were run without blindfolds, an important experiment control that was introduced at a late date in this study). Thus, the final experiment.served to iteratively test and repair taux.

In order to address the intention to demonstrate the value of taux for iterative development and analysis, the following approach is suggested. The experiment would be run with another group of subjects. Condition B1 should be reverted, that is, to not use left/right signaling but to use all of the newer operational parameters (capture radius, sampling frequency and audio signaling frequency.) A new condition, B3, should be added to be identical to B1 but also to include the left/right signaling that indicates heading error direction. In this way, the effect of introducing the new display variation of left/right signaling can be appropriately assessed.

In addition to the changes in operating parameters described above, changes were made to the visual feedback condition. In order to address weaknesses with the visual condition employed in the test experiment, this condition (A0) was modified by replacing the screen display with a paper template mounted on the tablet. Additionally, the puck's datum was translated from its center to the front most central extent. Although this appeared to exhibit the expected improvement with some measures (AvgOTE and TimePerUnitDistPerWP), this improved condition still raises a concern. It is expected that sight will significantly aid the subject in guiding their motion, but the DistRatio measures collected do not support this. It was observed that subjects exhibited an unnatural dwell and some disorientation when arriving near (but not at) the waypoint. They expected the arrival signal, but did not receive it. The subsequent disorientation resulted in extraneous movement to correct for the error. A retrospective analysis of the path data shows that the combination of these two factors contributed to the low scores for the visual condition. In short, the experiment conditions changed the sighted condition from one of using sight to one of operating blind when at or near the target.

As in the case of varying the operational parameters, validating this new visual feedback method was more appropriately done with a second test experiment rather than an iterative experiment with comparisons to prior data. To adjust for the latest observed weaknesses, the following changes are suggested for the next iteration of experiments. One of several options exists. The current puck, an off-the-shelf component, is replaced by a specialized device that removes the ambiguity provided by the current configuration. A device with a clear lens containing cross hairs, like those found on some older drafting digitizers, is envisioned. Alternatively, or even in combination, the capture radius of the target can be relaxed. By allowing this relaxation, it is anticipated that performance would approach a Fitt's law type of motion that would be expected for the sighted condition.

8.3.2 Design of the Experiment

Based on the post hoc analysis, several questions are raised about the controls used for the experiment. Several controls could have been employed to reduce variation, but were overlooked. Three are suggested and discussed below. Next, this section considers selection of subjects. The selection employed was non-random and purposive, producing results that may not extrapolate to the intended real world population. This is discussed next. Finally, since people learn at different rates, control problems may be introduced if some subjects haven't fully learned a particular audio feedback condition. A discussion of these issues follows.

The size of relevant physical features of subjects was not captured and was not controlled for. Physical positioning was controlled to a degree, but not completely. More specifically, subjects come in all sizes and have all types of arm lengths. Subjects were seated, but the distance of the subject to the tablet on the table and table height was not controlled. Future experiments could limit selection of subjects to those with similar physical dimensions or could specify seating and tablet placement for the most relevant position variables.

There were no controls for handedness. Handedness was captured for demographic purposes, but not employed as a control. Specific paths, as designed, may have provided an advantage for either left or right handed subjects. Future experiments could limit the subject pool to right handed people. Or, more ambitiously, future work could assess the advantage of specific path geometry and alter appropriately for left and right handed subjects.

Finally, no control was performed for a subject's experience with stereo sound. It was observed that one subject was extremely comfortable with spatial audio (A1), while most did not exhibit this comfort level. Future experiments should consider a user's stereo experience through a questionnaire or by performing a simple test.

The selection of subjects for either test experiment was purposive and non-random. As a result, most had an advanced level of college education, used a computer about 6 hours a day and had an average age of about 44 years. Conversely, the intended consumer of the audio feedback studied averages 60-65 years old, has only a high school or bachelor's level education and may not use a computer at all. Therefore, the ability of the results to generalize to the intended population is not known., These factors may have enhanced the subjects' performance, in particular, in their use of the puck which is similar to a mouse. However, it may have also hurt their performance because the puck does not operate like a mouse and requires its users to understand that the orientation of the device is also an important parameter to control. This can only be found out by selection of a more representative sample..

Finally, this section considers the topic of learning. Training to a criteria performance level was not carried out in each of the conditions.. People learn differently and at different rates. They may also learn differently in different conditions, so there is likely to be an interaction effect of learning with a condition. This issue, in particular, needs to be addressed in future work. A possible solution would be to have subjects perform a set of tasks and require a certain performance level to be considered "learned" on each condition.

8.3.3 Research Methods

In the test experiment, it was determined that the time measure employed to assess subjects' performance was normalized for varying route distances but was not normalized for the varying number of waypoints in different trial geometries. In the final test experiment, this measure was modified to normalize for both distance and number of waypoints. This modification was performed for the time measure only; no accommodation was made to normalize the error measures (AvgOTE, AvgHE and DistRatio). Intuitively, this normalization makes sense for the error measures and should be considered in the next iteration of experiments.

8.4 Summary

Summarizing, pair-wise comparisons showed that many of the expected relationships are supported, and departures exist for the four scenarios described above. User preferences were consistent with anticipated results in the case of A2 v. A1 and not consistent for B2

v. B1. Possible explanations were provided. A discussion of problems with the experiment followed. The results of the pair-wise comparisons and discussion of problems with the experiment suggest areas of further inquiry in continued and future work.

CHAPTER 9

CONCLUSION

9.1 Summary

This thesis presented the design and development of an evaluation system for generating audio displays that provide feedback to users engaged in performing navigational tasks. It first developed the need for such a system by describing existing wayfinding solutions for visually impaired and blind users, investigating new electronic location-based methods that have the potential of changing these solutions and surveying existing research conducted on relevant audio information representation techniques. An evaluation system that supports the manipulation of two basic classes of audio display is then described.

Based on prior work on wayfinding with audio display, research questions are developed that investigate the viability of different audio displays. These questions are used to generate hypotheses and to develop an experiment which evaluates four variations of audio display for wayfinding. Comparison to a baseline condition using visual feedback was also performed. A test experiment with sighted subjects was performed; opportunities for improvement were identified and implemented. A final experiment which tests these hypotheses on sighted users wearing blindfolds was then conducted.

Results from the experiment show that spatial audio combined with spoken hints is the better than spatial audio without the assistance. Also, support for suppression of pitched feedback during on-target navigation was not found. Overall, the experiment demonstrates the viability of the prototyping tool for testing multiple different audio display combinations for navigational tasks. A discussion of contributions and future work was provided.

In summary, a system has been developed for the evaluation of audio feedback used during navigational tasks. The experiments conducted demonstrate that the system is viable. The system provides a sturdy foundation to modify and test existing sound mechanisms, to implement new navigational events and new sounds mechanisms, and to integrate entirely new subsystems. A case study was provided where audio displays were constructed, evaluated and iterated using the evaluation system. This work presents an opportunity for future researchers to build on this foundation and experience and to identify new sound mechanisms that can help those desiring to accomplish navigational tasks using sound.

9.2 Audio Feedback Design Recommendations

Many walkthroughs of the system have been conducted with informants. A pilot experiment was run with three subjects, a test experiment with eight subjects, a validation experiment with five subjects and the final test experiment with ten subjects. Based on these experiments, multiple observations can be made about what is known about audio feedback and navigational events while wayfinding. These observations are provided below along with evidence to support the claims. In all cases, this evidence is provided anecdotally, however, it is believed that further processing of the experiment data would substantiate the claims.

9.2.1 Observations About Navigation Events

The system, as implemented, supports the capture of information on a selected set of events that occur during the lifecycle of a navigation task. Note that these events could have been parsed or aggregated differently. The events are based on earlier work by others as well as their definition constituting one of the contributions of this research. The navigation events are: navigation started, on course, off course, waypoint arrival, and navigation ended. Additionally, the event model tracks if the navigator has passed their destination and also supports a fine grained “warning” indicator for a state that exists between on course and off course. The supported events appear to map to the navigator’s mental model, since evidence supports that they recognize themselves in these states and act appropriately. The following discussion follows a navigator along a navigation task to illustrate the states and the supporting evidence.

First, consider the ‘navigation started’ state. In this state, subjects have no idea in what direction the next waypoint is located and begin to search for it. While in this state, subjects will pan with the puck or pause to listen for guided assistance (the strategy varies depending on the condition.) The data, if analyzed for this evidence, would show increased heading error and a low velocity while in this state. Once the wayfinder achieves receives discrete feedback and recognizes the ‘on course’ state, they change their behavior and proceed toward the waypoint. This is evidenced by decreased heading error and increased velocity. While ‘on course’, they continue to make positive progress towards the waypoint. High velocities continue to be observed. Periodic, discrete feedback reinforces the ‘on course’ state and results in continued forward movement.

Next consider the ‘off course’ state. If a heading error threshold is reached, the subject is presented with appropriate discrete feedback. The feedback is signaled periodically while they remain in this state. Subjects are observed as altering their behavior by ceasing to make forward progress and panning the puck to return to an on target condition.

After returning to ‘on target’ and successfully arriving at a waypoint, subjects acknowledge this condition by acting as they did previously in the ‘navigation started’ state. They again pan or listen for assistance for the next objective. Should a subject pass a waypoint without meeting the arrival criteria, they are observed to take one of two courses of action. If the feedback communicates this state, they turn or back up. In conditions that do not communicate this state, subjects proceed away from the destination until it becomes clear that they have past it.

Having followed a navigation task, several observations can now be made. The event model, as implemented, appears to map well to the wayfinder’s mental model of the task. In the literature reviewed, such a model was not found. This model within taux serves a basis for navigational events and can be extended for additional states as needed. One such example is suggested next.

One state that the existing event model didn’t fully consider concerns distance to the current waypoint. It is observed that with several of the audio feedback conditions, that subjects sense their proximity to the waypoint and react when they are close to it. As they approach and receive feedback indicating that they are close, they reduce their velocity and proceed more cautiously. From the perspective of the measured data, their velocity decreases. When they are farther away, the existing navigational event model does not discriminate between varying degrees of distance. Providing more resolution in reporting of distance for this distant condition may provide more clues to the navigator and yield better performance. Discretizing the distance (far, intermediate and close, for example) and assigning representative feedback to each state may lend to the application of different audio mechanisms that perform particularly well in each of those particular conditions.

9.2.2 Observations About Audio Feedback

Several mechanisms were used to communicate information to the wayfinders about their navigation status. These are spatial audio, varying pitched tones, spoken assistance and selective use of silence. The tracking plots (Appendix R) and summary plots of descriptive statistics (Figure 7.3) are referenced to support the claims made here. Observations about each audio display are provided and overall recommendations follow.

Spatial audio provided useful assistance to most of the subjects, however, three found this display to be completely unusable. Conversely, two subjects preformed very well. Varying volume of the frequently displayed audio signal help subjects while close to the waypoint, but didn't help when they were farther away as the differences in volume for longer distances do not provide as much contrast. Augmenting spatial audio with spoken assistance improved navigation performance, suggesting that subjects responded well to the added information given about distance remaining.

Next, consider varying pitch. Although no planned comparisons were performed, it is useful to compare the varying pitch display (B1) with the spatial audio display (A1). This can be done by viewing the box plots in Table 7.3. In most measures, there is no notable difference, except for AvgHE. This suggests that this display method is effective at reducing a wayfinder's heading error. Also, consulting the tracking plots in Appendix R, it is estimated that the off target error is larger for B1 than for A1. (A root mean square (RMS) analysis could prove this.) Given these observations, it is suggested that varying pitch could be a component in an effective hybrid display model but probably does not stand well on its own.

Finally, silence was used in a selective condition to improve navigational performance. As described earlier (Chapter 8), the performance gains were not observed.

Additionally, in three cases, subjects commented that they didn't like the silent feedback condition.

9.2.3 Overall Recommendations

Based on the observations of the previous sections, two suggestions for improvements for audio displays emerge.

First, a hybrid model utilizing multiple audio display methods is suggested. For example, different displays may be employed if the subject is close, far or at an intermediate distance from the location. Second, it is suggested that multiple information cues be combined to communicate more information within the signaling. For example, a signal with varying pitch might be combined varying volume and occasional spoken hints to provide a richer status to the wayfinder.

Two other suggestions are offered here. Even with this highly portable and rapid prototyping system, a significant investment in time and energy is required to set up an experiment, even with a small number of users such as ten. It is recommended that implementation of the suggested hybrid displays be performed on a very small set of users first. Then, once evaluated, these can be iterated or taken to a larger set of subjects for data collection and analysis. Secondly, the displays considered here are a first attempt and meant to demonstrate the capabilities of taux. Other displays should be contemplated and evaluated that move well beyond this simple pallet of spatial audio, spoken hints, and varying pitch.

9.3 Limitations of this Research

This research has a major limitation which should be noted. This work demonstrates that people are able to perform assigned navigation tasks on the tablet device. This demonstration, however, is not guaranteed to be applicable to the more general case, that is, the case for which it is intended to serve. It is not concluded that this system and its derivative displays will generalize for visually disabled people navigating in the real world. Additionally, even if it did meet that burden, it may then fail to generalize when more complex audio environments are introduced. Examples of this audio complexity would include traffic noise, sound reflections, conversations, or other ambient noise.

It is possible that there may be another application where this work can be more directly applied. This application is in the realm of the desktop computer. Perhaps taux could be employed to help develop audio displays that help computer users navigate on their computer's screen, allowing them to navigate within their desktop computer environment. Here is how this might work. People need to learn the layout of the screen. Audio landmarks, representing points of interest on the screen, could be represented in taux as waypoints. Users could explore the screen and navigate to these points of interest using audio guidance as defined within and evaluated by taux. One example of a candidate display method can be found in Friedlander Schlueter & Mantei (1998), where the user can navigate circular menus effectively while receiving audio feedback. In another example, Donker, Klante & Gorny (2002) present three dimensional auditory objects in front of the user and use a torch metaphor to only expose those items within certain proximity. Many possibilities exist and taux is well situated to implement and evaluate different displays. This topic is referenced again in the Future Research section.

9.4 Future Research

Based on the developments and the findings of this work, many opportunities exist for continued research. These are listed as follows:

9.4.1 More Work with Learning Assessment

It was observed in both the test experiment and final experiment that subjects exhibited improved performance over time due to learning. The experiment method was modified to include counterbalancing, minimizing the possibility of ordering effects. Learning is also possible within a condition; training and practice were performed in order to minimize this effect during actual trials. The effectiveness of this practice has not been quantified and opportunity for improvement exists. Additional support comes from anecdotal evidence; one subject did exceptionally well with condition A1. Condition A1 is generally problematic for most users, while this user excelled with it. Upon further inquiry, it was identified that this subject uses equipment in their work life which is similar to the A1 feedback. This suggests that learning, possible over a long timeframe, may play a part in this subject's performance with condition A1. Further work is required to determine an appropriate assessment of learning. Once identified, the taux system should be easily modified to measure and expose relevant data.

9.4.2 Consideration of Valuable Subject Suggestions

Many subjects provided valuable suggestions during the experiment in the post-experiment questionnaire. These contemporaneous suggestions should be mined and evaluated. For example one subject suggested using a continuous Geiger counter sound to represent heading error. Several offered suggestions about the timing of feedback, that it should be modified to be less frequent or available upon query. Others suggested substituting non-speech audio sounds for audio messages in some cases. Careful consideration and iteration of ideas could result in significant navigational performance increases.

9.4.3 Full Scale Implementation

Several observations indicate that there are issues with measurement and generalization of the taux system. The implemented system can be easily adapted to permit substitution of the tablet device with a life-scale location sensing system.

9.4.4 Modify the Apparatus

Several observations also suggest that the off-the-shelf implementation of taux' location sensing system introduces some measurement and validity problems that may be remedied. Physical improvements, such as constraining the puck to only rotate about its defined pivot point or replacing it with a much smaller device with a more human-like form factor may result in a higher fidelity experience with less variability introduced by the apparatus.

9.4.5 Extend Event Model and Exploration of Hybrid Sound Models

In the process of the test and final experiments, it was evident that subjects become very disoriented when passing a destination. Recovery from this condition is usually not instant and pays a heavy toll on the performance data. Modify taux' event model to signal this condition and assigning sound behaviors to its occurrence is one possible extension of the event model that would yield significant benefit. It is suspected that there are others as well. Future work should implement this event and related sound behaviors. Continued work should also consider other potential events as well. It was observed in the test and final experiments that some conditions appear to behave differently based on the distance of the subject to the destination. For example, a pitched representation of heading error is more sensitive when closer to the target. By analyzing the strengths and weaknesses of competing display mechanisms, there may be an opportunity to mix and match based on a subject's proximity to the target. Accordingly, the event model could be expanded to include navigation events such as 'entered short range', 'left short range', entered 'very long range', etc.

9.4.6 Add and Evaluate a Driving Lane Model

Several subjects expressed dissatisfaction over the sensitivity of the reporting under the pitched sound conditions (B1 and B2). A suggested improvement would be to relax the model and not report based on bearing to the destination's exact coordinates, but, rather, to attempt to keep the traveler within a 'driving lane' that parallels the scheduled path on either side and adjust the output accordingly. This would allow greater error with the heading error measure, but would attempt to constrain the subject to navigate within symmetric 2D planar tolerance of the scheduled path. Construction of this condition would need to be performed and evaluated.

9.4.7 Improve Measures

It was observed that heading error provided a useful comparison of audio feedback conditions, but fell short when expected comparisons to the visual feedback condition yielded unexpected results. A candidate explanation has been provided. Further study could evaluate the use of this measure and identify opportunities for improvement. For example, accumulated heading error could be tallied for a given trial. Additionally, this work could be combined with a life-scale implementation and evaluated there as well.

9.4.8 Study Effects of Poor Precision on Navigation

The evaluation system as currently implemented assumes that the location of the destination and of the traveler is known with a high degree of precision. In real navigation environments such precision is not practical and maybe not even possible. The location of the traveler, the destination or both could be subject to reporting errors. Such error could have an effect on the navigator, ranging from an annoyance to making a navigational aid unworkable. The taux system could easily be extended to implement this 'jitter' and the effects could be studied through trials.

9.4.9 Study Applicability of Navigation and Audio Feedback in Desktop Applications

Visually impaired and blind users continue to experience difficulty when navigating on desktop computers. Most interfaces are still inherently visual, and much of that experience translates poorly to non-visual adaptations. It is possible that the audio navigation tasks investigated in this work (or evolutionary follow-ons) could offer sound feedback mechanisms that permit better desktop navigation for visually impaired users. Further study in this area may result in significant improvements for this class of user.

9.5 Contributions

Several contributions are identified and detailed in this section.

First, this work presents a research tool. A reusable system has been produced that can be used to evaluate different audio feedback mechanisms used during navigational tasks. The work offers an underlying architecture which can be utilized immediately through the existing system implementation or can be easily extended to implement other systems. The system can be used as is, easily modified simply with the introduction of new sound mechanisms, or more profoundly changed with the introduction of new subsystems (location, GIS, and UI). Care was taken to establish documented and predictable interfaces at the subsystem level to facilitate adaptation.

Next, this work demonstrated the proposed system could be implemented. Once implemented, the system was exercised with ad hoc trials, pilot trials, a planned test experiment and a final study. This demonstration provides validation and provides a basis for carry-on work.

Several other contributions are noted as follows. A review of the literature revealed common measures employed and also identified a measure that could be adapted from related user interface research. This measure (heading error) proved useful for some comparisons, but exhibited weakness when using a baseline comparison. This development identifies an opportunity for refinement of this measure for future research.

An event model has been constructed and exposed for point to point navigation. Common conditions are identified such as: waypoint location unknown, waypoint location known, on course, slightly off course, off course, facing opposite direction, etc. More are envisaged, such as "subject passed waypoint." Such an event model was not found to be defined in the literature. With such a model, future work can easily assemble and assign new sound behaviors to known model events, resulting in new sound feedback mechanisms.

A major contribution of this work is the capability of the system to rapidly implement and evaluate new sound mechanisms for navigational feedback. Investigators from multiple disciplines such as psychology, orientation and mobility, or human computer interaction can come together to rapidly assemble and evaluate new mechanisms or to iterate and evaluate existing ones.

This work introduces a truly portable evaluation environment. Prior systems have done this either at real scale or in fixed simulation environments. A portable approach is potentially useful since candidate subjects may be remote and may have difficulty in traveling.

APPENDIX A

INTERVIEWER RECORD SHEET

This appendix contains a document used by the investigator during experiment trials. This record sheet contains subject information, visual acuity test results and an identifier for the condition sequence used. It provides a checklist of all steps that need to be conducted during the experiment. It also contains a notes section for any observations that are made within each condition.

Interviewer Record Sheet

Subject ID:
Subject Name: ______________________________
Subject Email: ______________________________
Interviewer Name: ______________________________
Date: ______________________________

Snellen Acuity 20' __________ 10' _________

Condition Sequence (Ring 1)

```
 1: A1 A2 A0 B1 B2
 2: A2 B1 A1 B2 A0
 3: B1 B2 A2 A0 A1
 4: B2 A0 B1 A1 A2
 5: A0 A1 B2 A2 B1
 6: B2 B1 A0 A2 A1
 7: A0 B2 A1 B1 A2
 8: A1 A0 A2 B2 B1
 9: A2 A1 B1 A0 B2
10: B1 A2 B2 A1 A0
```

Checklist

0) ____ Perform headset check - record volumes
Left _____ Right _____
1) ____ Check Windows settings for volume and balance
2) ____ Disable virus scanning on computer
3) ____ Consent form
4) ____ Study introduction
5) ____ Pre-questionnaire
6) ____ Subject training script and instructions for the experiment session
7) ____ Subject post questionnaire
8) ____ Subject debriefing form
9) ____ Arrange to get copies to subject

Notes

Condition _______

Training Time/ideal distance -- record times from spreadsheet
1.dat _____ _____ _____ _____ _____
2.dat _____ _____ _____ _____ _____
3.dat _____ _____ _____ _____ _____
4.dat _____ _____ _____ _____ _____
5.dat _____ _____ _____ _____ _____

Condition _______

Training Time/ideal distance -- record times from spreadsheet
1.dat _____ _____ _____ _____ _____
2.dat _____ _____ _____ _____ _____
3.dat _____ _____ _____ _____ _____
4.dat _____ _____ _____ _____ _____
5.dat _____ _____ _____ _____ _____

Condition _______

Training Time/ideal distance -- record times from spreadsheet

1.dat _____ _____ _____ _____ _____
2.dat _____ _____ _____ _____ _____
3.dat _____ _____ _____ _____ _____
4.dat _____ _____ _____ _____ _____
5.dat _____ _____ _____ _____ _____

Condition _______

Training Time/ideal distance -- record times from spreadsheet

1.dat _____ _____ _____ _____ _____
2.dat _____ _____ _____ _____ _____
3.dat _____ _____ _____ _____ _____
4.dat _____ _____ _____ _____ _____
5.dat _____ _____ _____ _____ _____

Condition ________

Training Time/ideal distance -- record times from spreadsheet

1.dat _____ _____ _____ _____ _____

2.dat _____ _____ _____ _____ _____

3.dat _____ _____ _____ _____ _____

4.dat _____ _____ _____ _____ _____

5.dat _____ _____ _____ _____ _____

APPENDIX B

IRB APPLICATION

The application that was approved by NJIT's Internal Review Board (IRB) is contained in this appendix.

PLEASE PRINT OR TYPE

Date: **January 19, 2007**

HUMAN SUBJECT RESEARCH REVIEW FORM
NEW JERSEY INSTITUTE OF TECHNOLOGY
INSTITUTIONAL REVIEW BOARD

Name of Principal Investigator(s): **Dr. Marilyn Tremaine, Professor Information Systems**
Robert J. Lutz, Ph.D. Candidate

NJIT Address: **4404 GITC Building, NJIT, Newark, NJ**

Department: **Information Systems Department**

E-mail Address: marilyn.tremaine@gmail.com, rl2@njit.edu

NJIT Affiliation (Check):

✓ **Faculty** ✓ **Student** ☐ Other

*Note students and doctoral candidate applying for IRB approval must submit written documentation from their faculty advisors (via e-mail) stating that research is being conducted under their supervision.

Project Title: **Investigation of Audio Feedback Mechanisms for Use in Wayfinding**

This project will be conducted:

☐ On Campus ☐ Off Campus ✓ **Both**

Is this research funded by outside source(s)? ☐ Yes ✓ **No**

If yes, indicate name(s) and type of funding source(s):

Name of Funding Source(s): ____________________

Type: ☐ Government (County, State or Federal) ☐ Foundation ☐ Corporation
☐ Other (Describe: ____________________)

Anticipated Starting Date of Project: **January 2007**

Anticipated Closing Date of Project: **August 2007**

Number of Subjects: **30**

NOTE: All principal investigators, faculty, and students who will be interfacing with human subjects in this study must complete an online training course in the protection of human subjects. This course can be accessed by going to the US Department of Health and Human Services' Office for Human Research Protection website (http://www.hhs.gov/ohrp/) and clicking on "Education." At the bottom of this page, you will see the tutorial for the training module for assurances. All certificates indicating course completion must be submitted with this application.

To Principal Investigator: In addition to the questions below, please furnish copies of any questionnaires interview formats, testing instruments or other documents necessary to carry out the research.

The completed forms should be sent to: Dawn Hall Apgar, PhD
dawn.apgar@njit.edu
Chair, IRB
DD Planning Institute – CABSR
Campbell 330
New Jersey Institute of Technology
University Heights
Newark, NJ 07102-1982

---

1. Project Title: **Investigation of Audio Feedback Mechanisms for Use in Wayfinding**

2. List the names and status (faculty, student, etc.) of the persons conducting the research:

    a. Principal Investigator(s):
    Dr. Marilyn Tremaine (faculty)
    Robert J. Lutz (student)

    1. Other Members of Research Team:
    n/a

    2. NJIT Faculty Advisor(s) if Student Project:
    Dr. Marilyn Tremaine

3. Describe the objectives, methods and procedures of the research project. This summary will used to describe your project to the IRB. Use up to 2 pages, if necessary. You may also attach a copy of an abstract or full research proposal describing this work.

    The purpose of this study is to evaluate different audio mechanisms used to guide blind individuals in navigating to a specific landmark. The study will evaluate both the quality of the path taken by a participant (how much deviation occurred) and the ability of the participant to form a mental model of their environment (what is located where and which paths intersect). A variety of audio mechanisms have been developed for wayfinding, but no comparisons have been made that judge the efficacy of one method over another. Rather than building an expensive sound enhanced environment for a blind participant to navigate, this research asks the participant to navigate in a virtual environment by moving a tracking device on a computer tablet. Via this method a variety of sound feedback mechanisms can be inexpensively tested. The study will require a participant to move the tracking device toward intermediate targets while being guided by non-speech audio and speech feedback. Sighted users also navigate on the tablet via visual feedback on the computer display for the purpose of collecting benchmark data. A total of 12 or 15 wayfinding tasks will be given to each study participant. In each task, the participant will need to navigate through 3 to 5 intermediate waypoints.

    A further description of the detailed design of this experiment is attached.

4. List name and institutional affiliation of any research assistants, workers student that will be working on this project.

Department of Information Systems, New Jersey Institute of Technology

5. If research assistants, workers, students will be working on the project describe their qualifications, special training and how they will be supervised.

The IRB certificates of Robert Lutz are attached with this submission. Dr. Marilyn Tremaine's IRB certificates are also attached.

6. What is the age of the subjects and how will they be recruited?

Subjects will include 15 sighted users as well as 15 visually impaired users and blind users.

Sighted subjects will be recruited through advertisements on campus and through social connections. The campus advertisement is attached. All sighted subjects are expected to be over the age of 18.

Visually impaired and blind subjects will be adults, age 18 and above.

Visually impaired subjects will be recruited through *New Jersey Commission for Blind and Visually Impaired* and through the *National Federation for the Blind.* The advertisement is attached with this application. This advertisement will also be distributed electronically so that it can be read by a screen reader and via Braille and large print flyers at local meetings for blind and visually impaired individuals.

7. Attendant risks: Indicate any physical, psychological, social or privacy risk or pain, which may be incurred by human subjects, or any drugs medical procedures that will be used. (This includes any request for the subjects to reveal any embarrassing, sensitive, or confidential information about themselves or others.) Also, indicate if any deception will be used, and if so, describe it in detail. Include your plans for debriefing.

Subjects will be asked to use the developed information browsing system to retrieve geographical information and to navigate within the virtual environment. They will be asked to give us their opinions about the system design.

No psychological, social or privacy risk will be incurred by human subjects in our study. No deception will be used.

Physical risks are not anticipated.

When our study is finished, subjects will receive a report of our study results (i.e. the optimized way to design the information browsing system for visually impaired users based on the study results).

8. Evaluate the risks presented in 7.
   a. Is it more that would normally be encountered in daily life?

      No.

   ♌ Do your procedures follow established and accepted methods in your field?

Yes.

9. How will the risk be kept at a minimum? (e.g. describe how the procedures reflect respect for privacy, feeling, and dignity of subject and avoid unwarranted invasion of privacy or disregard anonymity in any way.) Also, if subjects will be asked to reveal any embarrassing, sensitive, or confidential information, how will confidentiality of the data be insured? Also include your plans for debriefing. If subjects will be placed under any physical risk, describe the appropriate medical support procedures.

   Users are to be debriefed via the attached debrief script. Blind and visually impaired participants will have the debriefing script read to them. There will be a sighted friend or companion of the blind participant present throughout the entire study. This person will receive a printed version of the debriefing script.

10. Describe the benefits to be derived from this research, both by the subject and by the scientific community (this is especially important if research involves children).

    The most significant contribution that would come from this work is the generation of a more comprehensive auditory feedback mechanism for real-time wayfinding for blind individuals. Such a system can work in the small and guide a blind user along a curved sidewalk but also work in the large guiding a blind user to a key but distant location, e.g., the subway station.

    A secondary contribution would be the potential application of this research to stationary settings in which a blind user could explore an environment before traversing said environment.

11. Describe the means through which human subjects will be informed of their right to participate, not to participate, or withdraw at any time. Indicate whether subjects will be adequately informed about the procedures of the experiment so that they can make an informed decision on whether or not to participate.

    For all blind participants, we will have a companion or friend accompany the participant throughout the study. We will read the consent form out loud to the participant with the companion observer present. Appropriate pauses will be made in this reading to ensure that the potential participant has adequate time to understand their rights regarding consent. Sighted subjects will be given the consent form to read.

    The consent form will first give an introduction of the goal of the study and describe the detailed procedures and the approximate time needed for the study. Each potential participant will be fully informed of his or her rights regarding participation. Attestation of consent will be performed by a sighted observer for all blind participants.

    Subjects' participation is voluntary and based on their interest in the research project. Subjects may discontinue participation at any time. There is no penalty or loss of benefits for refusing to participate or discontinuing participation.

12. Complete the attached copy of the Consent Form and the Institutional Review Board will make a determination if your subjects will be at risk. This Consent Form must include the following five pieces of information: (1) The purpose of the research, (2) the procedures involved in the work, (3) the potential risk of participating, (4) the benefits of the research, (5) that the subjects are free to withdraw from the research at any time with no adverse consequences.

    The consent form is attached.

13. Furnish copies of questionnaires, interview formats, testing instruments or other documents to carry out the research. If questionnaires are not complete please submit an outline of the questions to be used. You will have to submit the completed questionnaire to the Committee before the research can begin.

    The documents include the following:

    1) Subject recruitment advertisement
    2) Consent form
    3) Study introduction
    4) Subject pre-questionnaire (there are two versions, see discussion below)
    5) Subject training script and instructions for the experiment session
    6) Subject post questionnaire
    7) Subject debriefing form
    8) Acuity test procedure and script

    Subjects will use either a "Sighted User" or a "Visually Impaired User" pre-questionnaire. Selection of the questionnaire will be made based on the subject's visual capability. Any user who is *visually impaired* or *legally blind* will use the "Visually Impaired" instrument, all other subjects use the "Sighted User" instrument. Definitions for *visually impaired* and *legally blind* follow guidelines provided by The New Jersey Commission for the Blind and are available at http://www.state.nj.us/humanservices/cbvi/faqdetail.html#require **(as retrieved 20 Feb 2007, FAQ #1).**

    During sighted subjects' participation, the subjects will read documents No. 2 to 6 by themselves.

    During visually impaired subjects' participation, these documents will be read clearly and slowly by the experimenter. A sighted companion of the participant will be given the written document that they can used to follow along with the reading. The experimenter will make sure the subjects follow and understand the reading.

14. If the subjects will be minor children, complete Consent Form as prescribed in paragraph 12 for signature by parent or guardian. If the project is approved (regardless of the Board's determination concerning risk), it will be necessary that a Consent Form be secured for every minor child.

    N/A

15. Attach copy of permission of facility to conduct the proposed research (if other that NJIT).

    N/A

APPENDIX C

CONSENT FORM

Each subject is required to agree to and complete a consent form prior to participating in any experiment. This appendix contains the consent form used by all subjects.

NEW JERSEY INSTITUTE OF TECHNOLOGY
323 MARTIN LUTHER KING BLVD.
NEWARK, NJ 07102

CONSENT TO PARTICIPATE IN A RESEARCH STUDY

TITLE OF STUDY: **Investigation of Audio Feedback Mechanisms for Use in Wayfinding**

RESEARCH STUDY:

I,______________________________________, have been asked to participate in a research study under the direction of **Dr. Marilyn Tremaine and Robert Lutz.** Other professional persons who work with them as study staff may assist to act for them.

PURPOSE:

The purpose of this study is to investigate the use of audio feedback mechanisms in the understanding of a surrounding environment. More specifically, this study considers the task of navigation in an environment. This navigational task is also referred to as *wayfinding*.

BENEFITS:

Two positive outcomes of this research are possible. First, identification of a new and better auditory feedback mechanism can help blind people with real time wayfinding. Second, the new mechanism could also help a stationary blind person explore an environment before starting to navigate.

DURATION:

My participation in this study will last for **no more than one hour and forty five minutes.**

PROCEDURES:

I have been told that, during the course of this study, the following will occur:

NOTE: for blind subjects, this information read; for sighted subjects, this information will be given to them in written form.

1. **I will be given an introduction to the study (before filling out this Consent Form).**
2. **I will be given information about my rights regarding consent to participate in this study and asked to sign a consent form if I agree to do so.**
3. **I will be trained in using a computer drawing tablet and a puck. As I move the puck, I will receive auditory feedback on where I am on the computer tablet in relation to points on the tablet that I will be asked to find.**
4. **Once training is complete, I will be asked to find specific points on the computer tablet by moving the puck. I will use the auditory feedback to find these points.**

5. **Once I have completed the study, I will be asked my opinions about my experience in using the system.**
6. **I will then be read a set of questions (or given a questionnaire -- for sighted users) for which I will record my evaluation of the different audio feedbacks I received. I will then be given a detailed presentation of the purpose of the study. I will be given a printed or emailed (for blind participants) copy of this presentation. If a blind participant does not have email access, an alternate method of sharing can be requested and will be determined based on the specific circumstances.**

PARTICIPANTS:

I will be one of about **30** participants to participate in this trial.

EXCLUSIONS:

I will inform the researcher if any of the following apply to me:

I am under 18 years of age.

I am blind and do not have a sighted companion that will accompany me.

I am deaf.

RISKS/DISCOMFORTS:

I have been told that the study described above may involve the following risks and/or discomforts:

There are no known risks or discomforts.

There also may be risks and discomforts that are not yet known.

I fully recognize that there are risks that I may be exposed to by volunteering in this study which are inherent in participating in any study; I understand that I am not covered by New Jersey Institute of Technology's insurance policy for any injury or loss I might sustain in the course of participating in the study.

CONFIDENTIALITY:

I understand confidential is not the same as anonymous. Confidential means that my name will not be disclosed if there exists a documented linkage between my identity and my responses as recorded in the research records. Every effort will be made to maintain the confidentiality of my study records. If the findings from the study are published, I will not be identified by name. My identity will remain confidential unless disclosure is required by law.

VIDEOTAPING/AUDIOTAPING: (NEED TO INCLUDE ONLY IF APPLICABLE)

I understand that my navigation on the computer tablet will be recorded during the course of the study. These records will be stored for **three years** after the end of this project (**on August 31, 2007**). After that time, the records will be destroyed.

The records will be stored on a secure server at NJIT and will not be made available to anyone except the investigators **(Dr. Marilyn Tremaine and Robert Lutz)** who are involved in this research.

PAYMENT FOR PARTICIPATION:

I have been told that I will receive $**0** compensation for my participation in this study.

As an alternate form of compensation, I have the option to accept a tutorial and orientation for NJIT's AudioBrowser application (http://www.audiobrowser.org). AudioBrowser is a free downloadable application that provides the ability for a desktop computer to browse and read the New York Times via synthetic speech. The researcher will provide an introduction and orientation session for this application, assist with installation (if possible), and respond to any questions.

RIGHT TO REFUSE OR WITHDRAW:

I understand that my participation is voluntary and I may refuse to participate, or may discontinue my participation at any time with no adverse consequence. I also understand that the investigator has the right to withdraw me from the study at any time.

INDIVIDUAL(S) TO CONTACT:

If I have any questions about my treatment or research procedures, I understand that I should contact either principal investigator at:

Dr. Marilyn Tremaine
Robert Lutz
Information Systems Department
New Jersey Institute of Technology
323 Martin Luther King Boulevard
Newark, New Jersey 07102
Email: marilyn.tremaine@gmail.com, rl2@njit.edu
M. Tremaine Telephone 011 49 15152088188 *
R. Lutz Telephone: 908-764-1905

*** Marilyn Tremaine's phone number is an international number, since Germany is her current and primary country of residence. Germany is 6 hours ahead of Eastern Standard Time. Marilyn is available for calls 4AM - 4PM (local time, EST). Marilyn can initiate a call at an agreed to time to the subject if that is preferred. Please contact her at the listed email or Robert Lutz at the listed email or telephone number to coordinate.**

If I have any addition questions about my rights as a research subject, I may contact:

Dawn Hall Apgar, PhD
IRB Chair
New Jersey Institute of Technology
323 Martin Luther King Boulevard
Newark, NJ 07102
(973) 642-7616
dawn.apgar@njit.edu

SIGNATURE OF PARTICIPANT

I have read this entire form, or it has been read to me, and I understand it completely. All of my questions regarding this form or this study have been answered to my complete satisfaction. I agree to participate in this research study.

Subject Name: ____________________________

Signature: ____________________________
Date: ____________________________

SIGNATURE OF READER FOR PARTICIPANTS WHO ARE VISUALLY IMPAIRED

The person who has signed above, ____, has a visual impairment, I read English well and have read for the subject the entire content of this form. To the best of my knowledge, the participant understands the content of this form and has had an opportunity to ask questions regarding the consent form and the study, and these questions have been answered to the complete satisfaction of the participant (his/her parent/legal guardian).

Reader/Translator
Name: ____________________________

Signature: ____________________________
Date: ____________________________

SIGNATURE OF INVESTIGATOR OR RESPONSIBLE INDIVIDUAL

To the best of my knowledge, the participant, ______________________________, has understood the entire content of the above consent form, and comprehends the study. The participants and those of his/her parent/legal guardian have been accurately answered to his/her/their complete satisfaction.

Investigator's Name: ______________________________

Signature: ______________________________
Date: ______________________________

APPENDIX D

SUBJECT ADVERTISEMENT

This appendix contains the flyer was created for on-campus recruiting of subjects.

Would you like to evaluate state-of-art technology for pedestrian navigation?

Volunteers Needed!

What do you do?

Participate in an experiment. The test will use a state-of-the-art augmented reality environment to provide sound feedback mechanisms for pedestrian navigation.

Follow a prescribed set of tasks, taking approximately one hour.

Who's eligible?

Any sighted or visually impaired person. Persons must be 18 or older.

What's in it for you?

7. an opportunity to experience 3D audio and other feedback mechanisms in an augmented reality environment
8. an opportunity to contribute to a potential solution for pedestrian navigation for blind travelers

If you can help, please contact me at:

Bob Lutz
rl2@njit.edu
tel: 908-764-1905

APPENDIX E

STUDY INTRODUCTION

This appendix contains a one page summary document. This document is read by prospective subjects prior to participation in any experiment.

What you will do in this study

In this experiment, you will be given an electronic drawing tablet and an audio headset. You will have a small device that rests on top of the tablet. The location of this device (we call it a puck) is sensed by the tablet so that the tablet will know at all times where the puck is located. The puck is similar to a mouse but must be kept on top of the tablet if the tablet is to know where it is located.

You cannot see it, but there is an invisible map on the tablet with a path laid out that you are to follow with the puck. We are asking you to move the puck along the path by proceeding directly to the next location in the path. There will be turns in the path once you reach each intermediate location. The only way you can tell whether you are going in the right direction and towards the next location is by listening to the sounds that are played to you as you move the puck along the path. The sounds are designed to tell you where the destination that you are to find is located. It will be at the end of the path you are following. You will be trained in what each set of sounds means. You will be asked to wear a blindfold while listening to the sounds and moving the puck on the tablet.

There are multiple locations for each path. Once you arrive at one location, you will be informed that you have reached this location. You task will then be to find the next location, and so on. You will be given approximately 3-5 locations for each path traversal. We will ask you to perform a total of 12 to 15 exercises. A set of three exercises will use one type of sound. The second set of three exercises will use a second type of sound. The third set will use yet another type of sound. The purpose of this study is to determine how effective each type of sound is in helping you to find the locations.

This entire study will take approximately one hour and forty five minutes including the training you will undergo to learn the tasks and the sounds. Do you have any questions at this point?

APPENDIX F

STUDY INSTRUCTIONS

This appendix contains several sets of instructions. One set of instructions is included for each experimental condition. The instructions are read to each subject prior to conducting each condition within an experiment.

Subject Instructions

Subject Instructions

<<NOTE : In the following instructions, boldface text within << >> bracket pairs are meant as reminders to the investigator and not to be read aloud.>>

<<Reread the study introduction to the subject as a refresher. This is only required if some time has passed since the subject read/heard the intro.>>

This experiment will allow me to evaluate the use of different sounds to help people find desired destinations. Your participation will help me compare different sounds. Please note that some of the sounds may be difficult for you to use. I may not have designed the sounds properly so that they match the needs of all people. This is why I am running this study, to find out whether my sounds are helpful or not. If a set of sounds is difficult, please try to do the navigation as best as you can. If they are too difficult, let me know and we can go on to the next set of sounds.

In the following exercises, I'll ask you to move the puck from its current location to a new location based on the sounds you hear. We will do 5 exercises for each type of sound.

The tablet is directly in front of you. Please take a minute to become familiar with it. **<<Assist the subject with locating the device and finding the extents.>>** There is also a Puck device, as previously described. This is the puck device. **<<Assist the subject with the finding the puck device.>>** You will also be using an audio headset. You can adjust the volume by rotating the wheel in the cord. **<<Demonstrate for subject.>>**

Orienting Comment – avoid backward or lateral moves

Also, remember to use the toy car analogy.

<A1 Virtual Sound Exercise>>

<<Load training/BLOB2.dat route data>>

In this exercise, a sound will appear to be coming from a location on the tablet. In your headset, you'll hear the sound on your left if the destination is on or towards your left. Similarly, you'll hear the sound coming from the right if the destination is on your right. You are to turn the puck so that the sound seems to come from directly in front of you.

Let's try finding a destination now. Locate the puck at the bottom center area of the tablet, pointing it towards the top of the tablet. Note, the bottom edge is the one closest to you. **<<Note the piece of tape *and the fixture* on the tablet that marks the center >>** Try moving the puck just by rotating it.**<<Make sure that the subject is only rotating – no translation. Correct if necessary>>** The destination to move to is somewhere above the puck. It is the destination that is sending the sound that you are hearing. You should hear the sound move from your left ear to the center and then to the right ear (or the opposite way depending on which way you have moved the puck.) Try rotating the puck back and forth to make the source switch from your left ear to the center to your right ear and back. Identify the location of the sound and point the puck towards it.

Once you have pointed the puck towards the location of the sound (your destination), I'd like you to move the puck towards that sound. Please, don't start until I ask you to. It is best to move the puck slowly in that direction until you get better at hearing the location of the sound. While listening to the sound, try to keep the puck pointed at the sound's location. If the sound becomes stronger in one ear, turn slightly in that direction to center the sound and to stay on the path towards your destination. The sound will get louder in both ears as you approach the location. You will hear a signal announcing your arrival when you reach your destination. Please try moving forward now. **<<Watch the subject, confirm that they understand the directions.>>**

Once we start this exercise, a signal of 3 bells will indicate that you've reached the first location. This is the starting location for your travel. The sound will change, it will now appear to come from the next location you are to go to. Follow the same process, turning towards the location and THEN moving in that direction until you hear the signal that indicates that you have arrived at the next location. When you arrive you will hear one bell. This process is repeated for 3 to 5 locations. When you finish the entire route you will hear 3 bells and an announcement that you have finished.

<<Load training/1.dat route data>>. Let's try a practice exercise. There are 4 destinations to be found within this route. Please locate the puck at the bottom center of the tablet, pointing it away from you. **<<CONFIRM that the subject has accomplished this.>>** Now you may start.

Let's try another practice exercise. **<< Repeat for 3 routes. Use more if the subject doesn't exhibit proficiency with responding to the feedback.)) Use Load training/2.dat through training/5.dat route data >>**

Do you have any questions? **<<Answer and record with notes.>>**

Ok, great. **<<Load A1/trial/1.dat route data>>**. Now let's begin with the first exercise. This time, please move as quickly and accurately as possible. Please locate the puck at the bottom center of the tablet and proceed to the first location, first by rotating and then by moving in the proper direction. Please try to stay as close to the path as possible. You may begin.

<<Repeat 4 times with trial data A1/trial/2.dat through A1/trial/5.dat. Each time remember to remind the subject to
. locate the puck to the bottom center of the tablet.
. try to stay as close to the path as possible
. remember to turn then move FORWARD. Please avoid sideways movements
>>

<<A2 Virtual Sound + Corrective Hints Exercise>>

<<Load training/BLOB2.dat route data>>

In this exercise, a sound will appear to be coming from a specific location on the tablet. In your headset, you'll hear the sound on your left if the location is towards your left. Similarly, you'll hear the sound coming from the right if the location is on your right. You are to turn the puck so that the sound will be directly in front of you.

Let's try finding the source of the sound now. Locate the puck at the bottom center area of the tablet and point it towards the top of the tablet. Note, the bottom edge is the one that is closest to you. <<**Note the piece of tape *and the fixture* on the tablet that marks the center** >> Try moving the puck just by rotating it.<<**Make sure that the subject is only rotating – no translation. Correct if necessary**.>> The location generating the sound is somewhere above the puck on the tablet. You should hear the sound move from your left ear to the center and then to the right ear (or the opposite way depending on which way you're rotating the puck.) Try rotating the puck back and forth to make the source switch from your left ear to the center to your right ear and back. Identify the location of the sound and point the puck towards it.

Sometimes, you may be come disoriented or lost on the tablet. A helper is available in the system that can provide you with information to help you again find the location of the sound source. You will hear the help speak when you first start moving towards the location of the sound. The helper may also make suggestions on which way to turn, etc. if it thinks you have become lost. This is what the helper sounds like. <<**Signal the location helper from the User Interface.**>>. If you would like the helper to provide information at any time during your exercise, please say "help."

Once you have set the puck to point towards the source of the sound, I'd like you to move the puck towards the sound. Please, don't start until I ask you to. It is best to move the puck slowly until you get more comfortable with moving it towards a sound source. While listening, try to keep the puck pointed at the sound's location. If the sound becomes stronger in one ear, turn slightly in that direction to center the sound again and to stay on the proper path. The sound will get louder in both ears as you approach the location. Upon arrival at your destination, you will hear a signal announcing your arrival.

If you vary too far from the path, a message will be provided to help you get back on track and moving in the right direction. The message sounds like this. <<**Signal a veer correction message from the UI.**>>

Once we start the exercise, a signal of 3 bells will indicate to you that you've reached the first location. This is the starting location for your route. The sound will change. It will now appear to come from the next location in the route. Follow the same process you used to find the first location, turning toward the location and THEN moving in that direction until you hear the next signal. You will hear one bell. The process will be repeated for 3-5 locations. When you finish the route you will hear 3 bells and an announcement that indicates that you have finished.

<<**Load training/1.dat route data**>>. Let's try a practice exercise. There are 4 locations

to be found within this route. Please locate the puck at the bottom center of the tablet, pointing it towards the top of the tablet. <<**CONFIRM that the subject has accomplished this.**>> Now you may start.

Let's try another practice exercise. << **Repeat for 3 routes. Use more if the subject doesn't exhibit proficiency with responding to the feedback. Use Load training/2.dat through training/5.dat route data>>**

Do you have any questions? <<**Answer and record with notes>>**

OK, great. <<**Load A2/trial/1.dat route data**>>. Now let's begin with the first exercise. This time, please move as ***quickly and accurately*** as possible. Please locate the puck at the bottom center of the tablet and proceed to the first location, first by rotating and then by moving in the proper direction. Please try to stay as close to the path as possible. You may begin.

<<Repeat 4 times with trial data A2/trial/2.dat through A2/trial/5.dat. Each time remember to remind the subject to:
. locate the puck to the bottom center of the tablet.
. try to stay as close to the path as possible
. remember to turn then move FORWARD. Please avoid sideways movements. >>

<<A0 Sighted Users Navigating with Visual Feedback Exercise>>

<<Load training/BLOB2.dat route data>>

A black dot on the tablet shows the location you will need to move the puck to. You are to point the puck at the dot and move directly to it. You will first go to the stating location, marked with an "S"; then you will proceed throught the next point by following them in order. Specifically, point toward number "1" and move forward going straight, then turn towards "2" and follow the same process. The process is repeated until you've reached the highest number on the tablet. In this case, it is numbered 2.

Let's try to point the puck at the black circle labeled "S" now. Locate the puck at the bottom center area of the tablet, pointing it towards the top of the tablet. Note: the bottom edge is that part of the tablet that is closest to you. **<<Note the piece of tape *and the fixture* on the tablet that marks the center >>** Try moving the puck just by rotating it.**<<Make sure that the subject is only rotating – no translation. Correct if necessary.>>** The location you are trying to find is some distance away from you on the tablet. It is located above and to the left of the puck.

Once you have selected the correct direction, I'd like you to move the puck toward the black circle. Please, don't start until I ask you to. It is suggested that you begin by moving the puck slowly in the desired direction. While watching, try to keep the puck pointed at the location. You will hear a sound signal that indicates that you have arrived at the desired location. You will also hear a voice updating you with the location of the location on the tablet. For example, you will first hear "Arrived at the start point."

Once we start the exercise, a signal of 3 bells will indicate that you've reached the first location you are to navigate to. This will be the starting location for your route. Follow the previously described process, turning toward the location labeled "1" and THEN moving in that direction until you hear the a signal that indicating that you have arrived. You will hear one bell when you reach each intermediate destination. You are to find between 3 and 5 destinations. When you arrive at your final destination, you will hear 3 bells and an announcement that indicates this.

<<Load training/1.dat route data>>. Let's try a practice exercise. There are 4 locations to be found within this route. Please locate the puck at the bottom center of the tablet, pointing it away from you. **<<CONFIRM that the subject has accomplished this.>>** Now you may start.

Let's try another practice exercise. **<<Repeat until timing for 3 locations within a route are within 1 second of each other ((for "training to criteria" purposes.)). Use training/2.dat through training/5.dat route data>>**

Do you have any questions ? **<<Answer and record with notes.>>**

OK, great. **<<Load A0/trial/1.dat route data>>**. Now let's begin with the first exercise. This time, please move as quickly and accurately as possible. Please locate the puck at the bottom center of the tablet and proceed to the first point, first by rotating and then by moving in the proper direction. Please try to stay as close to the path as possible. You may begin.

<<Repeat 4 times with trial data A2/trial/2.dat through A2/trial/5.dat. Each time remember to remind the subject to:
. locate the puck to the bottom center of the tablet.
. try to stay as close to the path as possible
. remember to turn then move FORWARD. Please avoid sideways movements. >>

<<B1 Varying Pitched Sound Exercise>>

<<Load training/BLOB2.dat route data>>

In this exercise, varying sounds will be used to indicate how well you are pointed at a location on the tablet. If you are pointed directly at the location you will hear the highest pitch tone. It sounds like this. **<<Signal the highest pitch tone.>>** If you change your direction to point away from the destination, the tone will become lower **<<Signal the warning level tone.>>**. If you change your direction to point very far away from the destination, you hear an even lower tone **<<Signal the low tone>>**. If you are pointed to the left of the destination, you will hear the tone predominately in your right ear. Consider the outdoor bug light zapper, you want to fly (or move toward) the higher pitches when you hear the signal.

Let's try to find the target now. Locate the puck at the bottom center area of the tablet, pointing it toward the top of the tablet. Note: the bottom edge is that part of the tablet that is closest to you. **<<Note the piece of tape *and the fixture* on the tablet that marks the center >>** Try moving the puck just by rotating it.**<<Make sure that the subject is only rotating – no translation. Correct if necessary.>>** The destination you are to move your puck to is located somewhere above the puck. You are to use the sound feedback to find this destination. You should hear the tone change as you rotate the puck. Try rotating the puck back and forth to make the tone switch from low to high to low. Finding the highest tone, identify the location of the sound and point the puck towards it.

Once you have selected a direction, I'd like you to move the puck towards that sound. Please, don't start until I ask you to. It is best if you begin by moving the puck slowly in the direction of your destination until you get better at hearing the location of the sound. While listening, try to keep the puck pointed at the location by keeping the tone's pitch at its highest value. If the pitch drops, try turning the puck to make it return to the higher value and to stay on the proper path. You will be given a signal to indicate that the puck has arrived at the desired location.

Once we start the exercise, a signal of 3 bells will note that you've reached the first location. This is the start point for your travel. The sound will now appear to come from the next location you are to navigate to in the route . Follow the same process, turning the puck towards the location and THEN moving in the direction of your destination until you hear the arrival signal. You will hear one bell. This process is repeated for 3-5 destinations. When you finish the entire route, you will hear 3 bells and an announcement to indicate that you have completed the route.

<<Load training/1.dat route data>>. Let's try a practice exercise. There are 4 locations to be found within this route. Please locate the puck at the bottom center of the tablet, pointing it towards your starting location**<<CONFIRM that the subject has accomplished this.>>** Now you may start.

Let's try another practice exercise. << **Repeat for 3 routes. Use more if the subject doesn't exhibit proficiency with responding to the feedback. Use Load training/2.dat through training/5.dat route data>>**

Do you have any questions? **<<Answer and record with notes.>>**

OK, great. **<<Load B1/trial/1.dat route data>>**. Now let's begin with the first exercise. This time, please move as quickly and accurately as possible. Please locate the puck at the bottom center of the tablet and proceed to the start location, first by rotating and then by moving in the proper direction. Please try to stay as close to the path as possible. You may begin.

<<Repeat 4 times with trial data B1/trial/2.dat through B1/trial/5.dat. Each time remember to remind the subject to:
. locate the puck to the bottom center of the tablet.
. try to stay as close to the path as possible
. remember to turn then move FORWARD. Please avoid sideways movements. >>

<<B2 Varying Pitched Sound w/Silence for On Course Exercise>>

<<Load training/BLOB2.dat route data>>

In this exercise, a sound will be used to indicate whether you are pointed at a location on the tablet. If you are pointed at the location you will hear the highest pitched tone. It sounds like this. <<**Signal the highest pitch tone**.>> If you change your direction to point away from your target destination, the tone will become lower <<**Signal the warning level tone.**>>. If you change your direction to be pointed very far away, you will hear an even lower tone <<**Signal the low tone**>>. If you are pointed to the left of the destination, you will hear the tone predominately in your right ear. Consider the outdoor bug light zapper, you want to fly (or move toward) the higher pitches when you hear the signal. Additionally, if you are pointed directly at the location, you will hear NOTHING.

Let's try one now. Locate the puck at the bottom center area of the tablet, pointing it toward the top of the tablet. Note: the bottom edge is that part of the tablet that is closest to you. <<**Note the piece of tape *and the fixture* on the tablet that marks the center** >> Try moving the puck just by rotating it.<<**Make sure that the subject is only rotating – no translation. Correct if necessary**>> The location you want to find is somewhere above the puck. You should hear the tone change as you rotate the puck. Try rotating the puck back and forth to make the tone switch from low to high to low. Find the direction with NO SOUND and point the puck in that direction.

Once you have selected a desired direction, I'd like you to move the puck towards that location. Please, don't start until I ask you to. It is best if you begin by moving the puck slowly in the desired direction until you get better at hearing the location of the sound. While listening, try to keep the puck pointed at the destination by keeping the sound silent. It the tone appears, try turning back towards silence. If the tone lowers, try turning the puck to make it return to the higher value and then to silence to stay on the proper path. You will hear a bell signal indicating that you have arrived at your desired destination.

Once we start the exercise, a signal of 3 bells will note that you've reached the first location. This is the start point for your route. You will note that the sound pattern has changed and that it now comes from the next location in the route you are to follow. Follow the same process, turning the puck towards the location and THEN moving in the direction of your desintation until you hear the next arrival signal. You will hear one bell. This process is repeated for 3-5 locations. When you finish navigating your route with the puck and arrive at your final destination, you will hear 3 bells and an announcement indicating this.

<<Load training/1.dat route data>>. Let's try a practice exercise. There are 4 locations to be found within this route. Please locate the puck at the bottom center of the tablet, pointing it away from you and towards your first destination. <<**CONFIRM that the subject has accomplished this.**>> Now you may start.

Let's try another practice exercise. << **Repeat for 3 routes. Use more if the subject doesn't exhibit proficiency with responding to the feedback. Use Load training/2.dat**

through training/5.dat route data>>

Do you have any questions ? <<**Answer and record with notes.>>**

OK, great. <<**Load B2/trial/1.dat route data**>>. Now let's begin with the first exercise. This time, please move as quickly and accurately as possible. Please locate the puck at the bottom center of the tablet and proceed to the first point, first by rotating and then by moving in the proper direction. Please try to stay as close to the path as possible. You may begin.

<<Repeat 4 times with trial data B2/trial/2.dat through B2/trial/5.dat. Each time remember to remind the subject to:
. locate the puck to the bottom center of the tablet.
. try to stay as close to the path as possible
. remember to turn then move FORWARD. Please avoid sideways movements. >>

APPENDIX G

BACKGROUND QUESTIONNAIRE FOR SIGHTED USERS

Prior to conducting an experiment, a background questionnaire is administered. This appendix contains the questionnaire that was constructed for administration to sighted subjects.

Background Questionnaire SU

The following questions ask you to tell us something about your background. This information will help us to understand the system design needs for different user groups. All information is completely confidential. You are free to decide not to answer any specific question.

Subject ID:______________________________ Today's Date: ____________

____

For the following set of questions, please indicate which of the answers best applies to you.

1. What is your age: _____

2. What is your gender ? __ M __ F

3. Could you tell me which education level best applies to you?
   a. ( ) high school b. ( ) 1-2 years university
   c. ( ) 3-4 years university d. ( ) advanced education beyond bachelor's degree

4. For approximately how many years have you been using a computer? ________________

5. What input devices do you use for your computer? Circle all that apply.

   __ Keyboard
   __ Mouse
   __ Microphone
   __ Joystick
   __ Touchpad
   __ Other input (Please explain) ______________________________________

6. In what ways do you get output from your computer? Circle all that apply.

   __ Speech output
   __ Visual display
   __ Sounds, e.g. beeps etc.
   __ Other output (Please explain)

   ____

7. On average, how many hours do you use a computer every day? ______________.

8. Below is a list tasks you might do with a computer. Please check off an item if you use a computer to do this task.
   ________ Create text documents
   ________ Manage text documents
   ________ Read news
   ________ Write emails
   ________ Use an online-chat program
   ________ Post messages on online bulletin board
   ________ Manage personal information such as contacts and appointments
   ________ Search the Internet
   ________ Develop web pages
   ________ Write software programs

9. Do you use a computer for any other activities besides the ones I have indicated? If so, what are they?

____
____
____

10. Do you have any hearing impairments? If so can you please describe them?

____
____
____
____

11a. Do you play a musical instrument ? __ Y __ N

11b. If so, for how long (years) ________

12. Are you left or right handed ? __ Left __ Right __ Ambidextrous

APPENDIX H

BACKGROUND QUESTIONNAIRE FOR VISUALLY IMPAIRED USERS

Prior to conducting an experiment, a background questionnaire is administered. This appendix contains the questionnaire that was constructed for administration to visually impaired subjects.

Background Questionnaire VIU

The following questions ask you to tell us something about your background. This information will help us to understand the system design needs for different user groups. All information is completely confidential. You are free to decide not to answer any specific question.

This questionnaire will be read to the user.

Subject ID:______________________________ Today's Date: ____________

For the following set of questions, please indicate which of the answers best applies to you.

1. What is your age? __________

2. Indicate subject's gender. __ M __ F

3. Could you tell me which education level best applies to you?

    a. ( ) high school b. ( ) 1-2 years university
    c. ( ) 3-4 years university d. ( ) advanced education beyond bachelor's degree

4. At what age did you become visually impaired? _______________

5. Which of the following best describes your ability to see ?

    ____ I see nothing, everything is the same
    ____ I can see shapes
    ____ I can see an object at arm's length
    ____ I can see well enough to avoid obstacles while traveling

6. What caused your vision impairment? ____________________

7. For how many years have you been using a computer? ________________

8. What software and hardware do you use to access information and computer programs? For example, JAWS.

____

9. How do you give commands to your computer?

    __ Regular keyboard
    __ Braille input
    __ Other input (Please explain)
    ____

10. How does your computer give you its output?

__ Speech Output
__ Braille Output
__ Other output (Please explain)
____

11. On average, how many hours do you use a computer every day? ________________.

12. Now you will hear a list of tasks you might do with a computer. Please say "yes" if you use a computer to do the task.

_____________ Create text documents
_____________ Manage text documents
_____________ Read news
_____________ Write emails
_____________ Use an online-chat program
_____________ Post messages on online bulletin board
_____________ Manage personal information such as contacts and appointments
_____________ Search the Internet
_____________ Develop web pages
_____________ Write software programs

13. Do you use a computer for any other activities besides the ones I have indicated? If so, what are they?

____
____
____

14. Do you have any hearing impairments? If so please describe them.

15. How often do you travel to new destinations in the city you live in ? ___________

16. How do you get to a new destination that you have never been to before? For example, once a week, twice a week, once a month, etc.

____

17. Do you travel on foot by by yourself ? __ Y __ N If so, how do you do this?

____

18. On average, how many times a week do you leave home? ________

19. Now you will hear a list of aids you may use for navigating. Please say "yes" if you use (or have used) any of these aids to do the task.

____________ Sighted guide
____________ Long cane
____________ Dog guide
____________ Tactile Maps
____________ Online services like Google Maps
____________ Electronic Travel Assistants
(a device reporting immediate obstacles using sound or touch)
____________ Navigational aids such as Trekker, StreetTalk, BrailleNote GPS

20a. Do you play a musical instrument? __ Y __ N

20b. If so, for how long (years) ________

21. Are you left or right handed? __ Left __ Right __ Ambidextrous

APPENDIX I

POST QUESTIONNAIRE

After the experiment is complete subjects are asked to complete a post-experiment questionnaire. This appendix contains this questionnaire.

Subject ID: ________________________
Date: ________________________

Post Questionnaire

Please select from one of the choices by circling the number for the best answer:

Example:
(1) I like Cheesecake :

Strongly Disagree	*Disagree*	*Neutral*	*Agree*	*Strongly Agree*
1	*2*	*3*	*4*	*5*

You would circle the number 5 if Strongly Agree was your answer.

1. I preferred hearing a sound at the location versus the varying pitch sounds.

Strongly Disagree	Disagree	Neutral	Agree	Strongly Agree
1	2	3	4	5

2. If I were lost in the woods, and all I had was a headset that played the voice speaking "Location, Location, ..." to guide me, it would help me ...

Very Much	Somewhat	Neutral	Not Much	Not At All
1	2	3	4	5

3. If I were lost in the city and became disoriented, and all I had was a headset that played the voice speaking "Location, Location, ..." to guide me, it would help me ...

Very Much	Somewhat	Neutral	Not Much	Not At All
1	2	3	4	5

4. If I were lost in the woods, and all I had was a headset that played varying pitch sounds to guide me, it would help me ...

Very Much	Somewhat	Neutral	Not Much	Not At All
1	2	3	4	5

5. When using the sounds with varying pitch, I preferred silence to a high pitch sound when I was facing my destination.

Strongly Disagree	Disagree	Neutral	Agree	Strongly Agree
1	2	3	4	5

6. I feel that either of the demonstrated methods (varying pitch tone or sound at the location) could allow me to find destinations in the real world.

Strongly Disagree	Disagree	Neutral	Agree	Strongly Agree
1	2	3	4	5

7. How do you compare these methods to find destinations with those you currently use for navigation in the real world ?

Better	Same	Worse
1	2	3

8. What methods do you use now to find a city street intersection if you are already on one of the cross streets?

9. Do you have suggestions for how I might improve the feedback sounds for finding destinations?

____

____

____

____

10. Please rank the following methods in order of preference:

_____ Spatialized audio
(voice speaking “Location, Location, ...)
_____ Spatialized audio with hints
(“Too far left”, “The location is to your right and in front of you”)
_____ Varying pitch
_____ Varying pitch with silence when on course

APPENDIX J

DEBRIEFING SHEET

After completing all the steps of an experiment, a subject is briefed about the nature of the work and is invited to ask questions or make suggestions. This appendix contains a single page summary for the subject to read (or have read to them) to stimulate the discussion.

Debriefing Sheet

Thanks for taking the time to participate!

As you have seen, several different sounds can be produced to help aid a person in locating a destination with sound. You've seen a few illustrated here, the actual number of sounds and techniques are virtually endless!

The purpose of this research is two fold: to explore new sounds for use while navigating and to develop a tool that can be used by other researchers to explore sound ideas of their own. In time, I hope to apply this tool to find good sound designs. Ultimately, new sounds will be discovered that describe information about places to people in a meaningful, convenient way.

This works assumes that work in other related areas will continue to improve and to be available in an inexpensive and universal way. These other areas include systems for mapping, systems for directions, headsets that don't interfere with the environment and good location sensing systems. Your assistance has contributed to the next generation of navigation systems for visually impaired people.

Thank you.

NOTE: The research group I belong to has developed a free newspaper reading tool. You can get more information about it and download it from www.audiobrowser.org. If you have questions or comments about it you can send email to help@audiobrowser.org or directly to me.

If you'd like to contact me:

Bob Lutz
rl2@njit.edu
telephone: 908-764-1905

Also, Dr. Tremaine's contact info is:
marilyn.tremaine@gmail.com
telephone: 732-445-5055

APPENDIX K

PROTOCOL FOR VISUAL ACUITY TEST

During the experiment session, each subject is asked to participate in a Visual Acuity test. The protocol follow is the Snellen Test; this appendix contains a document with the steps that the investigator uses to fulfill the test.

Test for Visual Acuity

The test used is the Snellen Eye Chart test.

(Bernell part number BC11931, www.bernell.com).

Text in *italics* is read by the investigator.made

(1)Place the Snellen chart on an open wall, where the top of the chart is 5' 6" from the floor
(2)Close any shades or curtains.
(3)Turn on all overhead lights.
(4) Measure a distance of 10' from the chart on the floor. Place a piece of tape there.
(5) Measure a distance of 20' from the chart on the floor. Place a piece of tape there.

Follow me and I will go through the vision test with you.

(1) Take the participant over to the eye chart test area.
(2) Line up their toes to the line on the floor (20').
(3) Participants can leave on their glasses if they wear them for driving.
Procedure: *Look at the wall and read aloud the smallest line you can comfortably read.*
(4) If the participant gets every letter on the first line they try correct have them try the next smaller line. Continue until they miss a letter. At that time, record the one that they were able to read in full (line above).
(5) If they get the first line they attempt incorrect, have them read the previous line. Repeat as needed until they get one line completely correct. Record this acuity.
(6) If the subject was unable to read any of the lines, repeat steps 1-5 at the 10' line

APPENDIX L

INVESTIGATOR'S PREPARATION CHECKLIST

Each experiment conducted in this work requires a combination of hardware, software, forms and miscellaneous items like masking tape and a tape measure. This appendix contains a checklist to be used by the investigator when preparing to conduct an experiment.

Investigator's Checklist
Preparation Steps Prior to Conducting an Experiment Session

Print out and bring:

- multiple copies of the consent form (at least 3, one for the subject, one for a witness, one for the investigator. Multiple copies should be provided to accommodate leaving a signed copy with the subject.)
- the interviewer's record sheet. (1 copy)
- pre-questionnaires (both SU and VIU, at least 2 each)
- post-questionnaires (at least 2)
- the Debrief Sheet. (at least 2)
- the subject instructions (1 copy for investigator)
- the Study Introduction (at least 2 copies)

Bring the following items:

- Tablet
- Puck
- Microphone
- Laptop
- Headphone splitter
- Headphones (2 sets)
- Headphone extension cord
- Extension cord
- Mouse
- Snellen visual acuity chart
- Tape measure
- Masking tape

APPENDIX M

SAMPLE COMMA SEPARATED TEXT FILE

Upon successful conclusion of a training or trial run within an experiment, the data is output to a comma separated value (CSV) text file. This appendix contains an example of this file.

```
"Subject","Subj005"
"Route data directory","C:\Documents and Settings\rlutz\My Documents\MyPrj\njit-repos-
taux\trunk\taux\route-data\A2\trial"
"Route data file","1.dat"
"Condition name","A2"
"written","2007-10-26_16-04-00"
"number of observations","508"
"total time (msecs)","96625"
"total distance traveled","35194.178240112225"
"ideal distance","21206.838684053742"
"distance ratio","1.659567404856817"
"average OTE","793.872564444989"
"average HE","0.18470178395655623"
"average velocity (tablet units/msec)","0.3642347036492856"
"average velocity normalized per segment (tablet
units/msec/segment)","0.1214115678830952"
"number of waypoints (includes start and end points)","4"
"arrival radius","375"
"svn rev","154:166"

"Waypoint","time (msecs)","min distance (tablet units)","time/minimum distance"
"1","1375.0","5000.155397585159","3.6364766527892067"
"2","2171.0","5000.466878202475","2.303301187564475"
"3","1688.0","5000.688452603301","2.962493159125178"

"waypoint","waypoint (x)","waypoint (y)"
0,11237,3899
1,11010,8894
2,9080,13507
3,4094,13890
"time","location (x)","location (y)","targetWaypoint","headingError","offTargetError",
1175373701875,11850.0,3800.0,1,1.410678054393479,620.9428315070559
1175373702062,11050.0,4100.0,1,0.008343569418790503,177.68207772683914
1175373702250,10550.0,4750.0,1,0.1105512777480815,647.657471118596
1175373702437,10200.0,5450.0,1,0.23099356096198204,965.5175921795501
1175373702640,10450.0,6100.0,1,0.1978084985738286,686.2662711757375
1175373702828,11000.0,6650.0,1,0.004456298486891051,111.8641233170749
1175373703015,11000.0,7200.0,1,0.005903119152105207,86.89489934849514
1175373703203,10950.0,8000.0,1,0.06701359804480406,100.52447574784334
1175373703390,10950.0,8600.0,2,0.3640975935390938,300.0599940011997
1175373703593,10950.0,9050.0,2,0.39725793202429555,4.859546236757561
1175373703781,11050.0,9450.0,2,0.4520455909239739,251.4965163517037
1175373703968,11050.0,9850.0,2,0.49412072356701986,405.8821004989003
1175373704156,11050.0,10100.0,2,0.5242518091098678,502.3730905908985
1175373704343,10950.0,10400.0,2,0.5417909820306864,525.9108927335471
1175373704546,10550.0,10900.0,2,0.5134269176211737,349.8873290465492 7
1175373704734,10400.0,11300.0,2,0.5390190343638911,365.8958342421242
1175373704921,10100.0,11700.0,2,0.5138858363859321,243.52726048607428
1175373705109,9800.0,12200.0,2,0.5035184897447718,159.75508276682356
1175373705296,9800.0,12600.0,2,0.67096483070424,314.1406669140225
1175373705500,9550.0,13200.0,3,1.4449978761709419,561.3813320729502
1175373705687,9050.0,13650.0,3,1.5224079780920512,140.28228445921405
1175373705875,8950.0,13650.0,3,1.5214131158903776,132.6233390233989
1175373706062,8250.0,13500.0,3,1.4772301015316576,70.5486861146769
1175373706250,7700.0,13450.0,3,1.4493776799957416,162.5260217074497
1175373706453,6800.0,13450.0,3,1.4096054123566497,231.4565306297878
1175373706640,6100.0,13450.0,3,1.35487375618566,285.0691486804938
1175373706828,5550.0,13550.0,3,1.341390707023773,227.48707718589836
1175373707015,5100.0,13750.0,3,1.4325194178909961,62.53978886390911

Investigator's notes (with timestamps) follow
"time","note"
"1175373705500", "investigator's cell phone rang"
```

APPENDIX N

R SOURCE FILES

Several R source files were created to facilitate the required statistical analysis required for data analysis. This appendix contains the source files used to perform the analysis. A sample data file is also included.

```
# calculate shapirowilk statistic for taux performance data
#
datafilename="taux-proposal-Summary.data"
tauxdata=read.table(datafilename,header=T)
names(tauxdata)


mywilk<-function(condition) {
    tmp<-subset(tauxdata,tauxdata\$Group==condition)
    tapply(tmp\$DistRatio, tmp\$Group, length)
}

grps=c("A0", "A1", "A2", "B1", "B2")


for (i in 1:length(grps)) {
       mywilk(grps[[i]])
}


tapply(tauxdata\$DistRatio, tauxdata\$Group, shapiro.test)
tapply(tauxdata\$AvgOTE, tauxdata\$Group, shapiro.test)
tapply(tauxdata\$AvgHE, tauxdata\$Group, shapiro.test)
tapply(tauxdata\$TimePerUnitDistPerWP, tauxdata\$Group, shapiro.test)
```

```
# calculate and plot the descriptive statistics for performance data
# collected from subjects while using taux
#
# description of variables
#======================
#SubjID                 a unique identifier representing each subject
#Group                  the condition, one of A0, A1, A2, B1, B2
#                       A0 = spatialized audio with visual feedback.
#                       A1 = Spatialized audio.
#                       A2 = Spatialized audio with hints.
#                       B1 = varying pitch
#                       B2 = varying pitch with silence during on-target condition
#DataFile               this is the data file used for the specific trial. each datafile
#                       contains a start point and
#                       3-5 locations that make op a route.
#TotalDist              this is the total distance traversed by a subject. Subject to
#                       approximation through periodic
#                       sampling. Sampling rate is 200 msecs during the experiment. These
#                       are reported in global
#                       coordinates for the taux system (currently tablet units)
#DistRatio              This is the ratio of the distance traveled divided by the ideal
#                       distance if the route were
#                       prefectly traversed.
#AvgOTE                 This is the average of all 'off-target' distances collected during
#                       the trial. These are
#                       sampled once every 200 msecs during the experiment. These are
#                       reported in global
#                       coordinates for the taux system (currently tablet units)
#AVGHE                  This is the average value  of all heading errors recorded during
#                       the trial. These are sampled
#                       once every 200 msecs during the experiment and reported in radians.
#TimePerUnitDistance    This measures the time the subject trook to traverse a particular
#                       trial. Since trial routes
#PerWP                  differ in length, the time is divided by the route length to
#                       normalize for comparison. This
#                       variable is reported in msecs/distance (distance in taux global
#                       coordinates)
#

datafilename="taux-proposal-Summary.data"
tauxdata=read.table(datafilename,header=T)
names(tauxdata)


tapply(tauxdata\$DistRatio, tauxdata\$Group, mean)
tapply(tauxdata\$DistRatio, tauxdata\$Group, sd)
tapply(tauxdata\$DistRatio, tauxdata\$Group, min)
tapply(tauxdata\$DistRatio, tauxdata\$Group, max)
tapply(tauxdata\$DistRatio, tauxdata\$Group, length)

tapply(tauxdata\$AvgOTE, tauxdata\$Group, mean)
tapply(tauxdata\$AvgOTE, tauxdata\$Group, sd)
tapply(tauxdata\$AvgOTE, tauxdata\$Group, min)
tapply(tauxdata\$AvgOTE, tauxdata\$Group, max)
tapply(tauxdata\$AvgOTE, tauxdata\$Group, length)

tapply(tauxdata\$AvgHE, tauxdata\$Group, mean)
tapply(tauxdata\$AvgHE, tauxdata\$Group, sd)
tapply(tauxdata\$AvgHE, tauxdata\$Group, min)
tapply(tauxdata\$AvgHE, tauxdata\$Group, max)
tapply(tauxdata\$AvgHE, tauxdata\$Group, length)


tapply(tauxdata\$TimePerUnitDistPerWP, tauxdata\$Group, mean)
tapply(tauxdata\$TimePerUnitDistPerWP, tauxdata\$Group, sd)
tapply(tauxdata\$TimePerUnitDistPerWP, tauxdata\$Group, min)
tapply(tauxdata\$TimePerUnitDistPerWP, tauxdata\$Group, max)

plotDepVar=function(depVarIndex, ylim, df) {
# df[,2] is the Group Column
# df[,5] is the DistRatio Column
# df[,6] is the AvgOTE Column
# df[,7] is the AvgHE Column
# df[,8] is the TimePerUnitDistPerWP Column
depVarName=names(df)[depVarIndex]
jpeg(file=paste(depVarName, "descstats.jpg", sep="-"))
bp <- boxplot(df[,depVarIndex]~df[,2], style = "tukey" , data=df,
      ylim=c(0,ylim), col="bisque", ylab=depVarName,
      main=paste("Descriptive Statistics for",  depVarName, sep=" "),
      sub="by Group")
mn.t <- tapply(df[,depVarIndex], df[,2], mean)
sd.t <- tapply(df[,depVarIndex], df[,2], sd)
xi <- 0.1 + seq(bp\$n)
points(xi, mn.t, col = "orange", pch = 18)
arrows(xi, mn.t - sd.t, xi, mn.t + sd.t,
       code = 3, col = "pink", angle = 35, length = .1)
legend(4,ylim, c("Mean", "Median", "Outlier", "Bounds 1 SD", "Bounds Q1/Q3", "Tukey
Fence"),
       cex=0.5,
       pch=c(18, -1, 1, -1, -1, -1),
       col=c("orange", "black", "black", "pink", "bisque", "black"),
       lty=c(-1, 1, -1, 1, 1, 2),
       lwd=c(-1, 3, -1, 1, 7, 1))
}

## library(lattice)
##attach(tauxdata)
plotDepVar(5, 6, tauxdata) # col 5 is DistRatio
plotDepVar(6, 3500, tauxdata) # col 6 is AvgOTE
plotDepVar(7, 2, tauxdata) # col 6 is AvgHE
plotDepVar(8, 2, tauxdata) # col 6 is TimePerUnitDistPerWP
dev.off()
```

```
# analysis and plot generation
# of questionnaire data from final experiment

# this data reflects subjects responses to questions about
# their preferences and beliefs about the condtions they
# participated in

q1=c(4,2,5,1,5,5,1,3,2,3)
q2=c(2,3,1,4,1,1,1,2,2,2)
q3=c(2,2,1,4,1,1,1,2,2,2)
q4=c(2,1,2,2,2,1,1,2,1,2)
q5=c(4,4,2,1,5,2,5,2,1)
q6=c(4,4,4,1,4,5,5,4,4,1)
q7=c(1,2,3,3,2,3,2,3,3,2)

jpeg(file="./questionnaire/q1.jpg", width = 602, height = 602)
cat("q1");mean(q1);t.test(q1,mu=3);q1
hist(q1,breaks=0.5+(0:5), col="grey", angle=45,
    xlab="Response (1=Strongly Disagree, 5=Strongly Agree)",
    main="Question 1: I preferred hearing a sound at the \n location versus the varying
pitch sounds"
    )
dev.off()

jpeg(file="./questionnaire/q2.jpg", width = 602, height = 602)
cat("q2");mean(q2);t.test(q2,mu=3);q2
hist(q2,breaks=0.5+(0:5), col="grey",
    xlab="Response (1=Very Much, 3=Neutral, 5=Not at All)",
    main="Question 2: If I were lost in the woods, and all \n I had was a headset
speaking \"Location, location, …\"\n to guide me, it would help me"
    )
dev.off()

jpeg(file="./questionnaire/q3.jpg", width = 602, height = 602)
cat("q3");mean(q3);t.test(q3,mu=3);q3
hist(q3,breaks=0.5+(0:5), col="grey",
    xlab="Response (1=Very Much, 3=Neutral, 5=Not at All)",
    main="Question 3: If I were lost in the city and became disoriented,\n and all I had
was a  headset that played the voice speaking \n\"Location, location, ...\" to guide me,
it would help me ….",
    )
dev.off()

jpeg(file="./questionnaire/q4.jpg", width = 602, height = 602)
cat("q4");mean(q4);t.test(q4,mu=3);q4
hist(q4,breaks=0.5+(0:5), col="grey",
    xlab="Response (1=Very Much, 3=Neutral, 5=Not at All)",
    main="Question 4: If I were lost in the woods, and all I had was a\n headset that
played vaying pitch sounds to guide me,\n it would help me ….",
    )
dev.off()

jpeg(file="./questionnaire/q5.jpg", width = 602, height = 602)
cat("q5");mean(q5);t.test(q5,mu=3);q5
hist(q5,breaks=0.5+(0:5), col="grey",
    xlab="Response (1=Strongly Disagree, 5=Strongly Agree)",
    main="Question 5: When listening to varying sounds, I \n preferred silence to a high
pitch when I \n was facing directly at the location"
    )
dev.off()

jpeg(file="./questionnaire/q6.jpg", width = 602, height = 602)
cat("q6");mean(q6);t.test(q6,mu=3);q6
hist(q6,breaks=0.5+(0:5), col="grey",
    xlab="Response (1=Strongly Disagree, 5=Strongly Agree)",
    main="Question 6: I feel that either of the demonstrated methods\n (varying pitch
tone or sound at the location)\n could allow me to find my destination in the real
world.",
    )
dev.off()
```

```
#example R data file (taux-Summary.data)
#
SubjID Group DataFile TotalDist DistRatio AvgOTE AvgHE TimePerUnitDistPerWP
19-Oct-2007-001 A2 A2-1.dat 30864.228612336483 1.455390361201951 945.6186747257952
0.3951702095584983 0.6196468127935093
19-Oct-2007-001 A2 A2-2.dat 36934.44114101095 1.4651038685385942 744.9638940710508
0.5468910742513117 0.5122129813921865
19-Oct-2007-001 A2 A2-3.dat 41557.33140482501 1.4045508682116483 754.3303433476397
0.47952789699570736 0.598642067647865
19-Oct-2007-001 B1 B1-1.dat 41089.746063871484 1.9333015785268306 1035.2143973565262
0.36721528520004293 0.5178494848935349
19-Oct-2007-001 B1 B1-2.dat 60863.514488061046 1.6051414920547902 1511.190930599487
0.5012787395668019 0.44496193625592884
19-Oct-2007-001 B1 B1-3.dat 43911.43445427942 1.7275952002527468 902.8631975752166
0.49866044385905994 0.4615372980881956
19-Oct-2007-001 A1 A1-1.dat 48061.74921902196 2.039317942495567 1350.2660727720593
0.8218369721592748 0.5672542958308402
19-Oct-2007-001 A1 A1-2.dat 58907.34985884144 2.035182362934518 1087.662971812213
0.6767821371006758 0.593487395897754
19-Oct-2007-001 B2 B2-1.dat 41991.507667627935 1.7343002150815543 951.2158903084879
0.3578336003931766 0.48451279349632426
19-Oct-2007-001 B2 B2-2.dat 43376.42130886167 1.4840194550204744 1098.1374875060544
0.4966014594636168 0.31400993791265736
19-Oct-2007-001 B2 B2-3.dat 58044.187544670785 1.84274831792286 1130.4368608564764
0.6801760792970465 0.3214417757955506
19-Oct-2007-001 A0 A0-1.dat 52526.87782636849 1.568664627960109 272.11910511988464
1.0622335536357144 0.21726086987566876
19-Oct-2007-001 A0 A0-2.dat 41029.086739208105 1.743525085558641 436.1027262526326
0.9054203334106062 0.2292951542879442
19-Oct-2007-001 A0 A0-3.dat 28962.728400113425 1.3373433329369808 285.3477470610899
0.5961425880432513 0.1986894425873666
21-Oct-2007-001 A0 A0-1.dat 77610.5077503335 2.3177630825195585 632.5117823759418
1.0946782896744274 0.2160483899695585
21-Oct-2007-001 A0 A0-2.dat 62516.69727772282 2.656637976438886 866.8615355850166
0.896967779546093 0.20638334504867006
21-Oct-2007-001 A0 A0-3.dat 37060.3691162384 1.7112489151260664 646.0037961821888
0.45827965331071563 0.18469852901451694
21-Oct-2007-001 A1 A1-1.dat 47882.548135906414 2.031714224569139 737.3816316050596
0.5227455693685251 1.1038732615206155
21-Oct-2007-001 A1 A1-2.dat 64531.898234478045 2.229504152677187 933.1517048750702
0.6728120370284093 0.856701415666218
21-Oct-2007-001 A1 A1-3.dat 95422.72991234787 3.605396873329347 934.1159648030339
1.5653793548615105 1.4636389259516467
…
```

APPENDIX O

USE CASE DESCRIPTIONS

This appendix contains a full listing of the use cases gathered during requirements elucidation for the evaluation system described in this work.

Table O.1 Pre-Experiment Verification Use Case

Use Case Name	**Pre-Experiment Verification**	
Related Requirements	C.4, E.3	
Goal in Context	The investigator establishes the experiment environment and checks for consistency with other experimental instances	
Preconditions	The system is operational and complete.	
Successful End Conditions	Investigator can navigate and confirms balanced feedback	
Failed End Conditions	Investigator can't navigate, no audio feedback, audio feedback is not in balance	
Primary Actors	Investigator	
Secondary Actors	None	
Trigger	Experiment with a subject is scheduled	
Main Flow	Step	Action
	1	Retrieve an existing route from the list of previously established routes
	2	Confirm navigation from the tablet with appropriate audio feedback for all audio modes
	3	Check the headset levels in both sides for a constant tone

Table O.2 Training Use Case

Use Case Name	**Training**	
Related Requirements	C.3, D.1, D.2, D.3, D.4, E.1, E.2	
Goal in Context	Subject navigates using a specific feedback condition until they are sufficiently familiar with the feedback.	
Preconditions	Pre-Experiment Verification and Configure Sound Feedback use cases completed	
Successful End Conditions	Subjects exhibits familiarity with the feedback condition	
Failed End Conditions	Subject is unable to navigate with the specified feedback condition	
Primary Actors	Subject	
Secondary Actors	Investigator	
Trigger	Experiment session started or prior experiment with different audio feedback method has completed.	
Main Flow	Step	Action
	1	Subject navigates route with audio feedback condition enabled
	2	Subject completes route
Extensions	Step	Action
	1	User is unable to complete route.
	2	Orientation is repeated, subject tries again or aborts.

Table O.3 Navigate Route Use Case

Use Case Name	**Navigate Route**	
Related Requirements	A.1, A.2, A.3, B.2 , D.2, D.3, D.4, E.1, E.2	
Goal in Context	Subject navigates using a specific feedback condition. Experiment data is collected.	
Preconditions	Subject training completed satisfactorily.	
Successful End Conditions	Subject completes navigation exercise.	
Failed End Conditions	Subject is unable to complete the navigation.	
Primary Actors	Subject	
Secondary Actors	Investigator.	
Trigger	Training completed.	
Main Flow	Step	Action
	1	New route data is loaded by Investigator
	2	Subject moves puck to home position
	3	Investigator signals the start of the trail.
	4	Subject navigates to first (start) point
	5	Subject arrives at start, data collection begins
	6	Subject navigates to intermediate route points
	7	Subject arrives at end, data collection stops
Extensions	Step	Action
	1	Subject Wanders out-of-bounds on tablet
	2	System signals "out-of-bounds" condition
	3	Subject returns within bounds
Extensions	Step	Action
	1	Exceptional event happens during experiment (phone rings, intruder enters room, etc.)
	2	Investigator describes event in text field in graphical user interface
	3	Event is entered into the longitudinal record for the experiment

Table O.4 Export Data Use Case

Use Case Name	**Export Data**	
Related Requirements	B.2, B.3, B.4, C.1, C.2	
Goal in Context	Experiment trial results are committed to disk for later processing	
Preconditions	Training Session or Navigate Route completes	
Successful End Conditions	Data written to spreadsheet and R input file	
Failed End Conditions	Write Fails	
Primary Actors	Investigator	
Secondary Actors	Subject	
Trigger	Training Session or Navigate Route completion	
Main Flow	Step	Action
	1	Investigator adds Subject Identifier in the graphical user interface
	2	Investigator commits the collected data through the graphical user interface
	3	Investigator confirms data write operation

Table O.5 Configure Sound Feedback Use Case

Use Case Name	**Configure Sound Feedback**	
Related Requirements	A.4, B.1	
Goal in Context	Investigator selects from a variety of system settings to define a sound feedback condition to be investigated.	
Preconditions	Pre-experiment validation complete.	
Successful End Conditions	Selection of desirable settings for a sound Feedback condition.	
Failed End Conditions	Inability to complete the selection.	
Primary Actors	Investigator	
Secondary Actors		
Trigger	Experiment in progress: Pre-experiment verification complete or completion of another sound feedback condition.	
Main Flow	Step	Action
	1	Investigator enters settings through the graphical user interface
	2	Investigator confirms settings by navigating on the tablet with the new condition active

Note: this step is detailed more fully in the Basic System Operation section.

Table O.6 Develop New Audio Feedback Mechanism Use Case

Use Case Name	**Develop New Audio Feedback Mechanism**	
Related Requirements	B.1	
Goal in Context	Investigator creates a new audio feedback mechanism for evaluation	
Preconditions	Pre-experiment validation	
Successful End Conditions	New audio feedback method is operational	
Failed End Conditions	Creation of new audio feedback mechanism not successful	
Primary Actors	Developer, Domain Expert	
Secondary Actors	Investigator	
Trigger	Interest in new exploration	
Main Flow	Step	Action
	1	Investigator enlists developer(s) and domain expert(s)
	2	Developer reviews this chapter
	3	New object class(es) are created to support the new behavior
	4	NavigationManager class and MainJFrame class are modified to include start/stop/edit operations for new class(es)
	5	Investigator confirms proper operation of new audio feedback mechanism

Note: this step is detailed more fully in the *Advanced System Operation* section.

APPENDIX P

SUBJECT TRACKING PLOTS FROM TEST EXPERIMENT

This appendix contains a compilation of all subjects navigation paths collected during the test experiment.

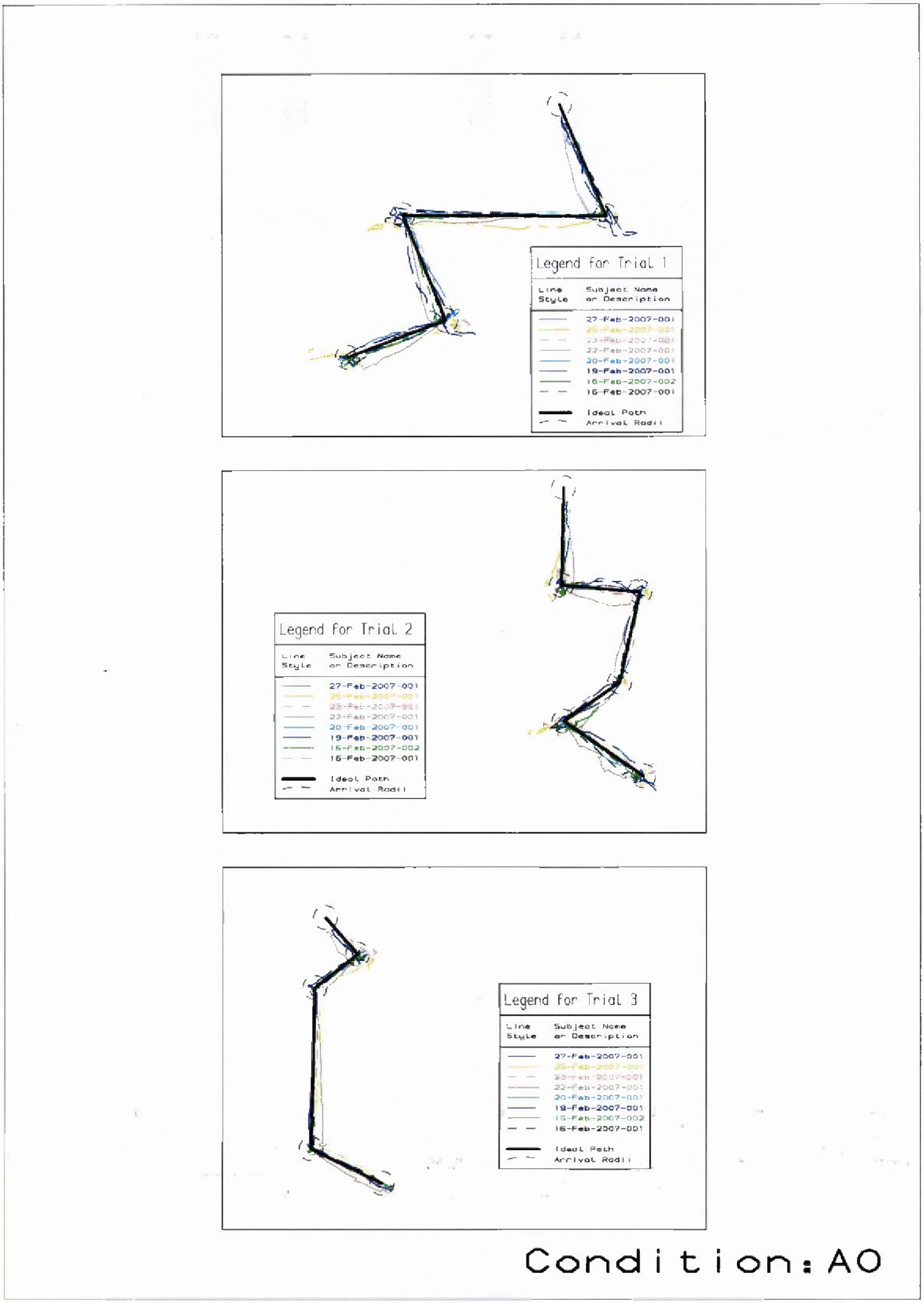


Figure P.1 Subject route data for condition A0.

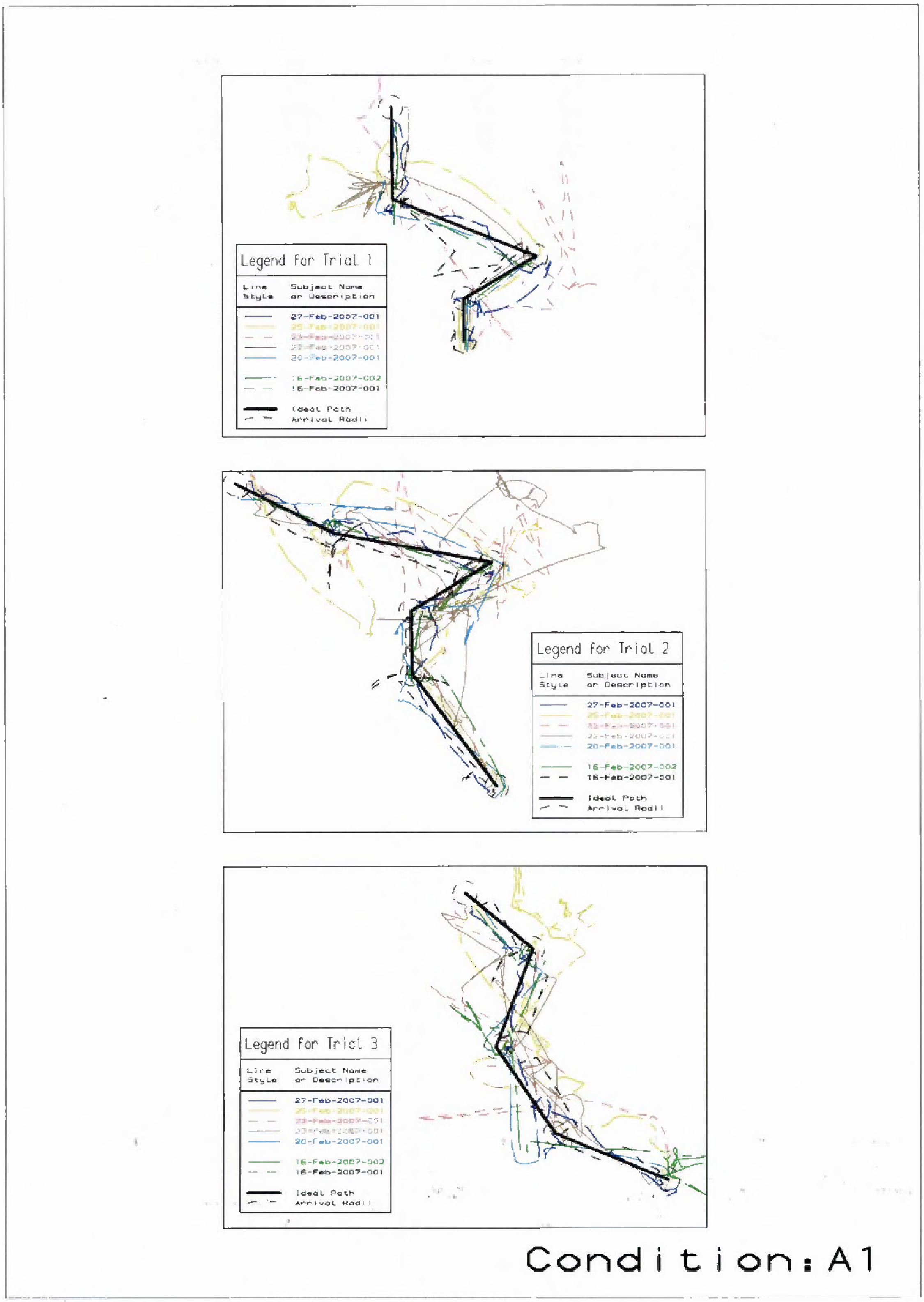


Figure P.2 Subject route data for condition A1.

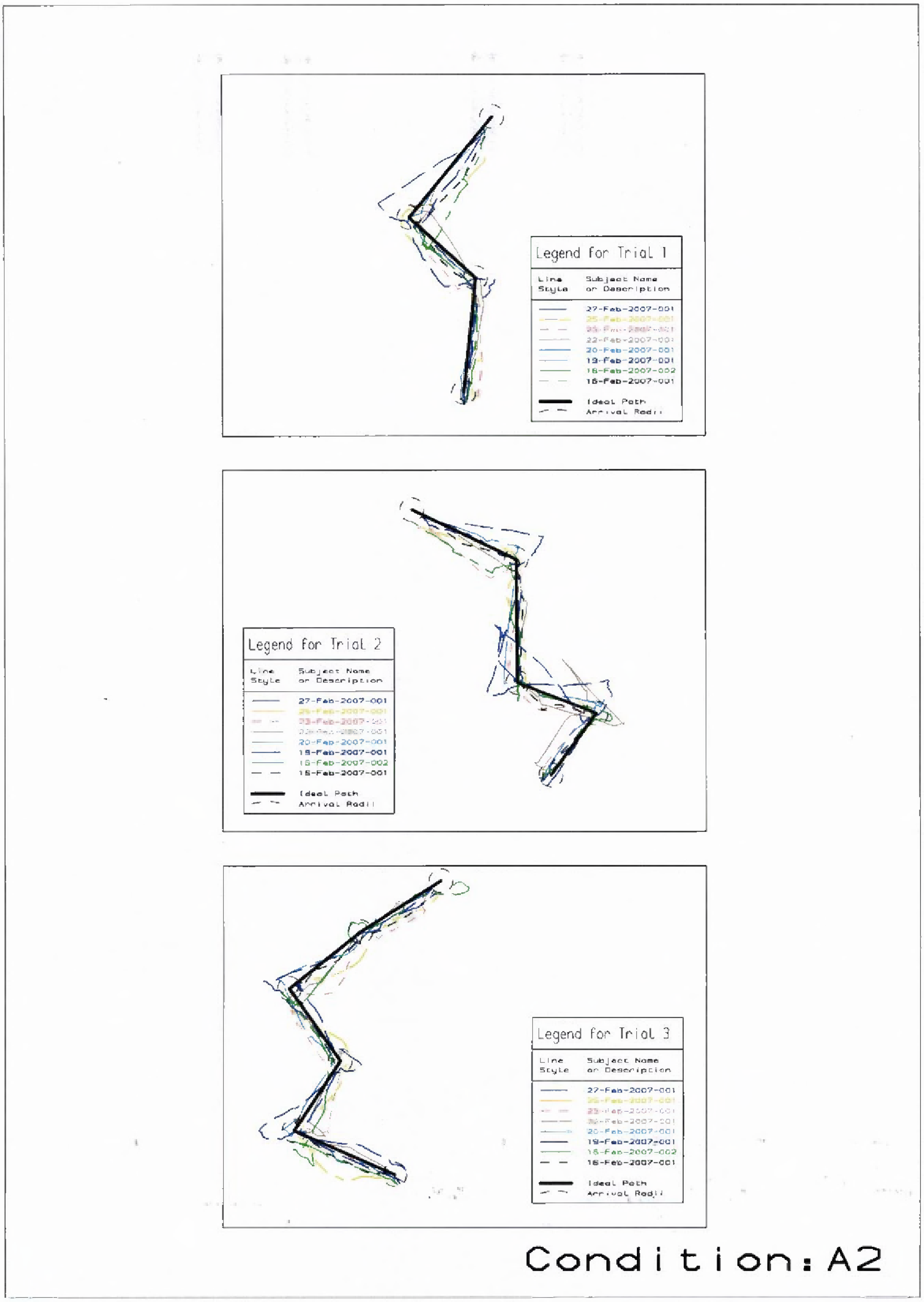


Figure P.3 Subject route data for condition A2.

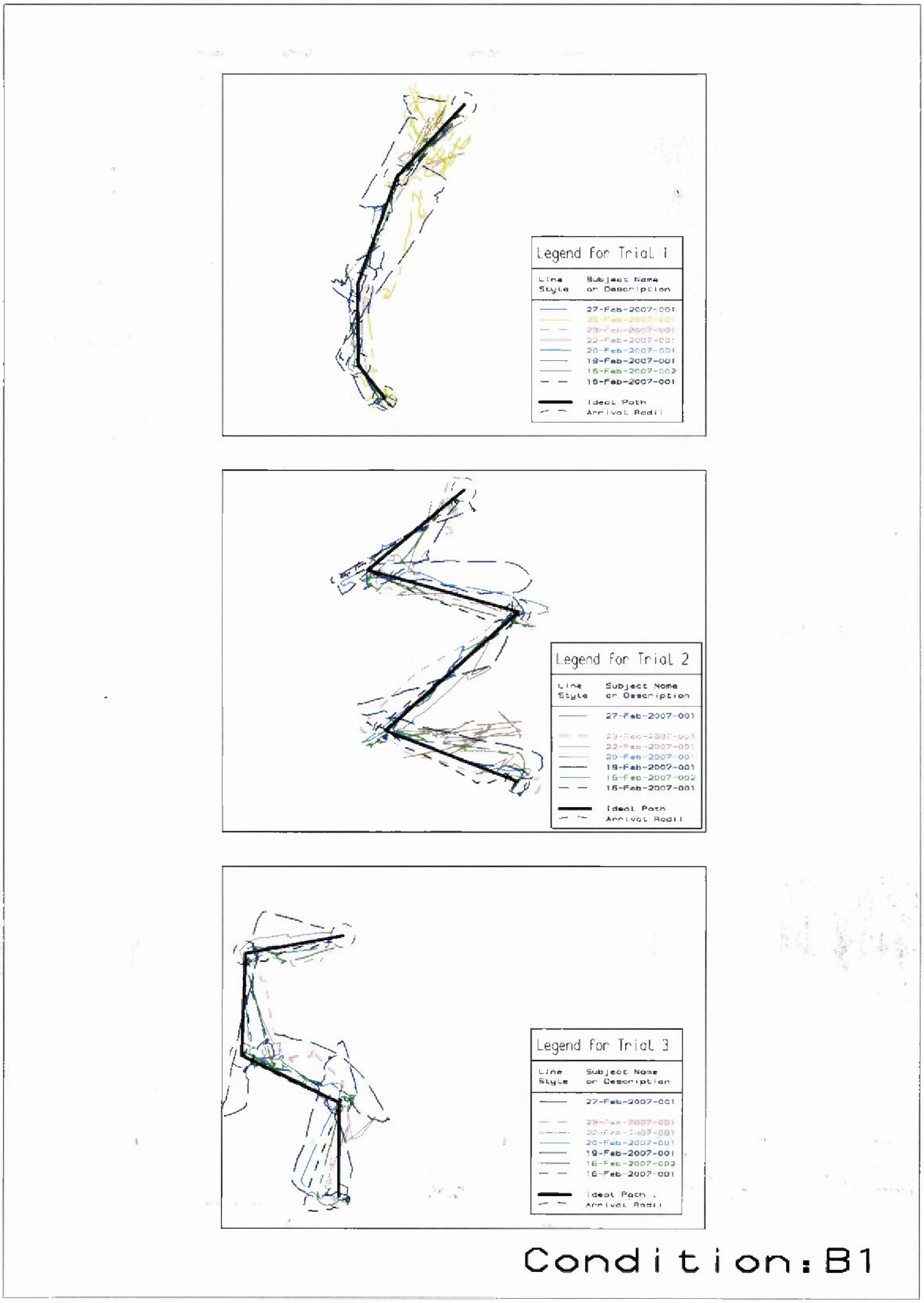


Figure P.4 Subject route data for condition B1.

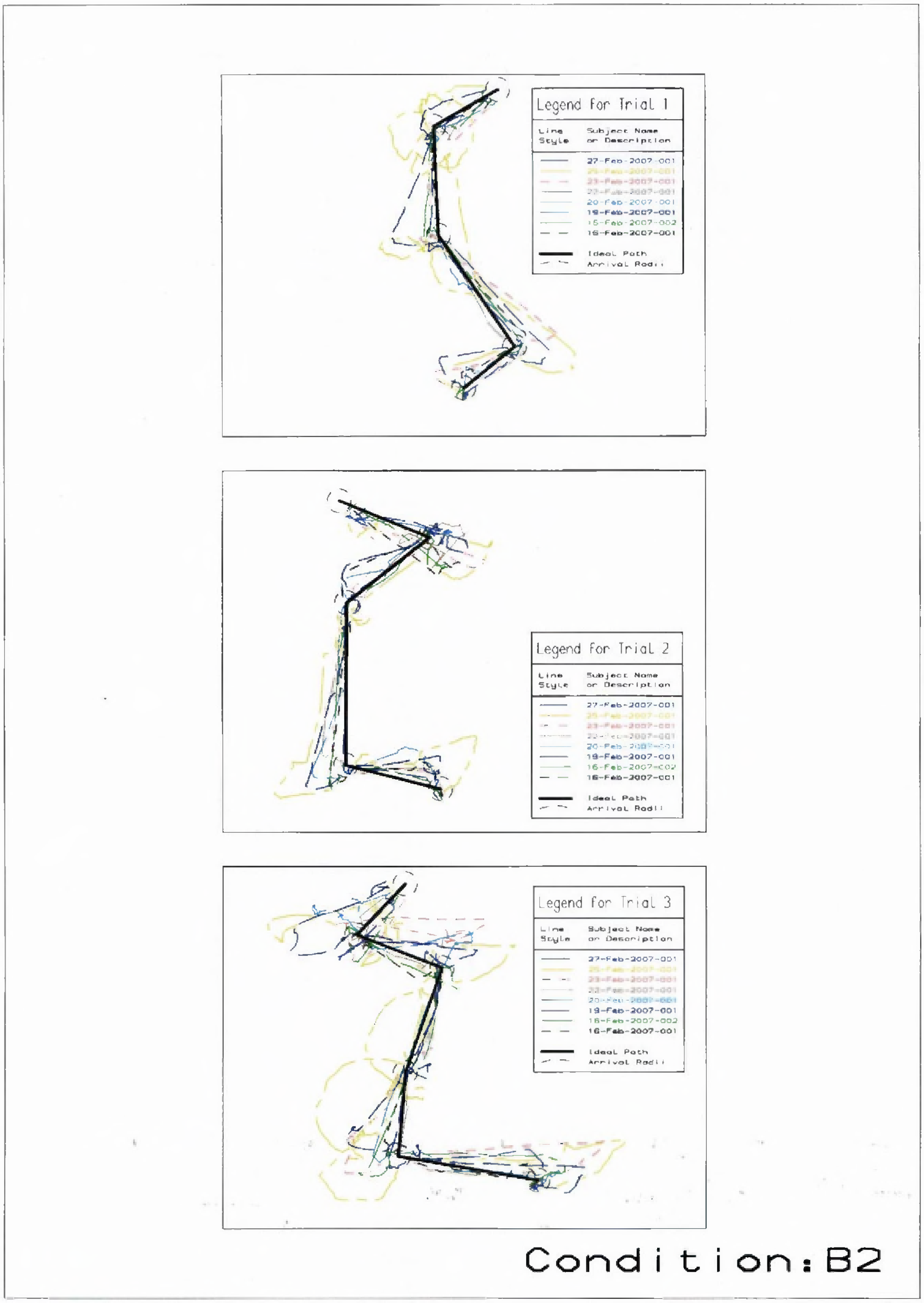


Figure P.5 Subject route data for condition B2.

APPENDIX Q

SUBJECT OFF TARGET ERROR AND HEADING ERROR DATA PLOTS

This appendix contains plots that display a subject's off target error and heading error as a function of time. Time is displayed both within trial and across trials. Data for all subjects is presented.

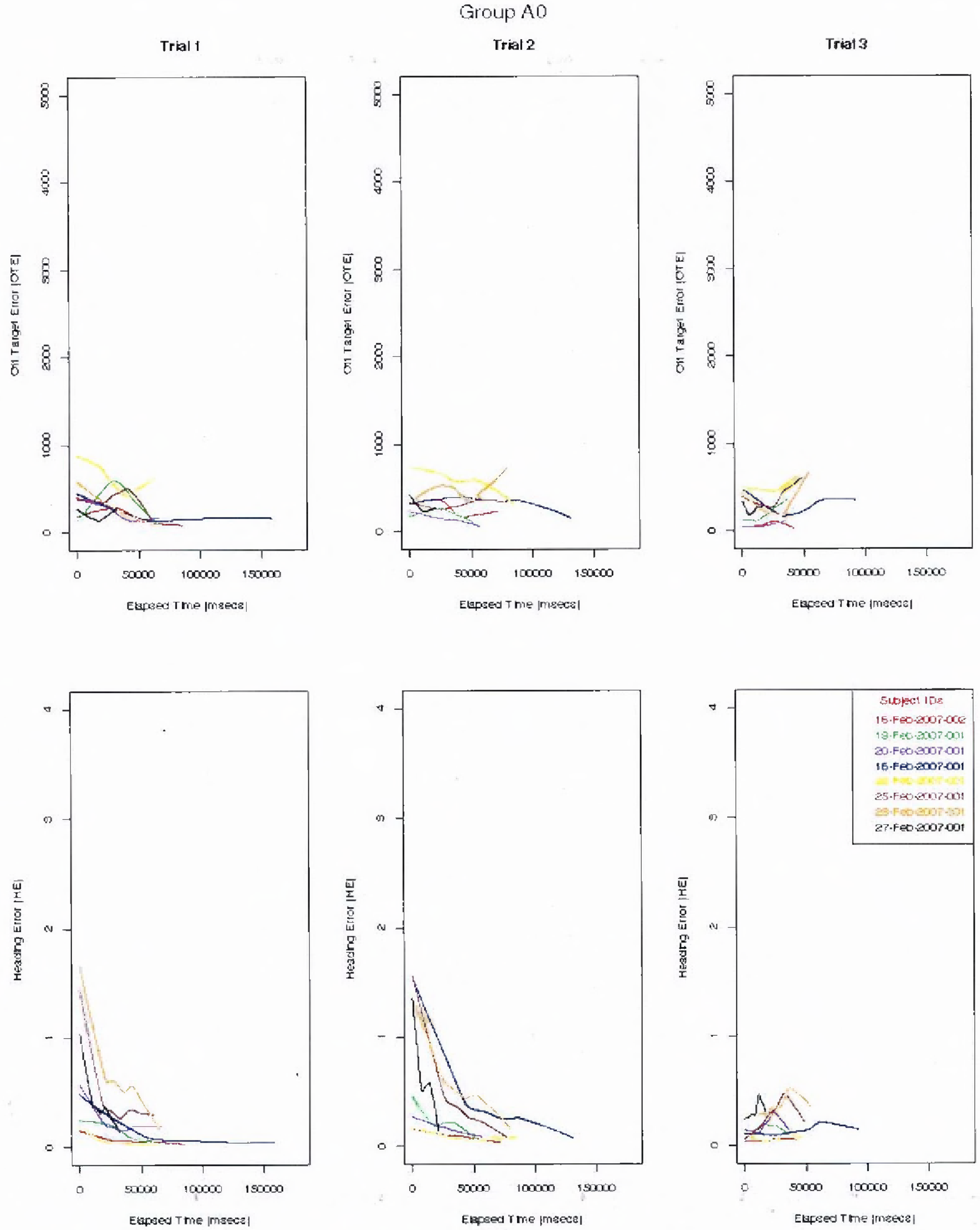


Figure Q.1 OTE and HE trends for all subjects – group - A0.

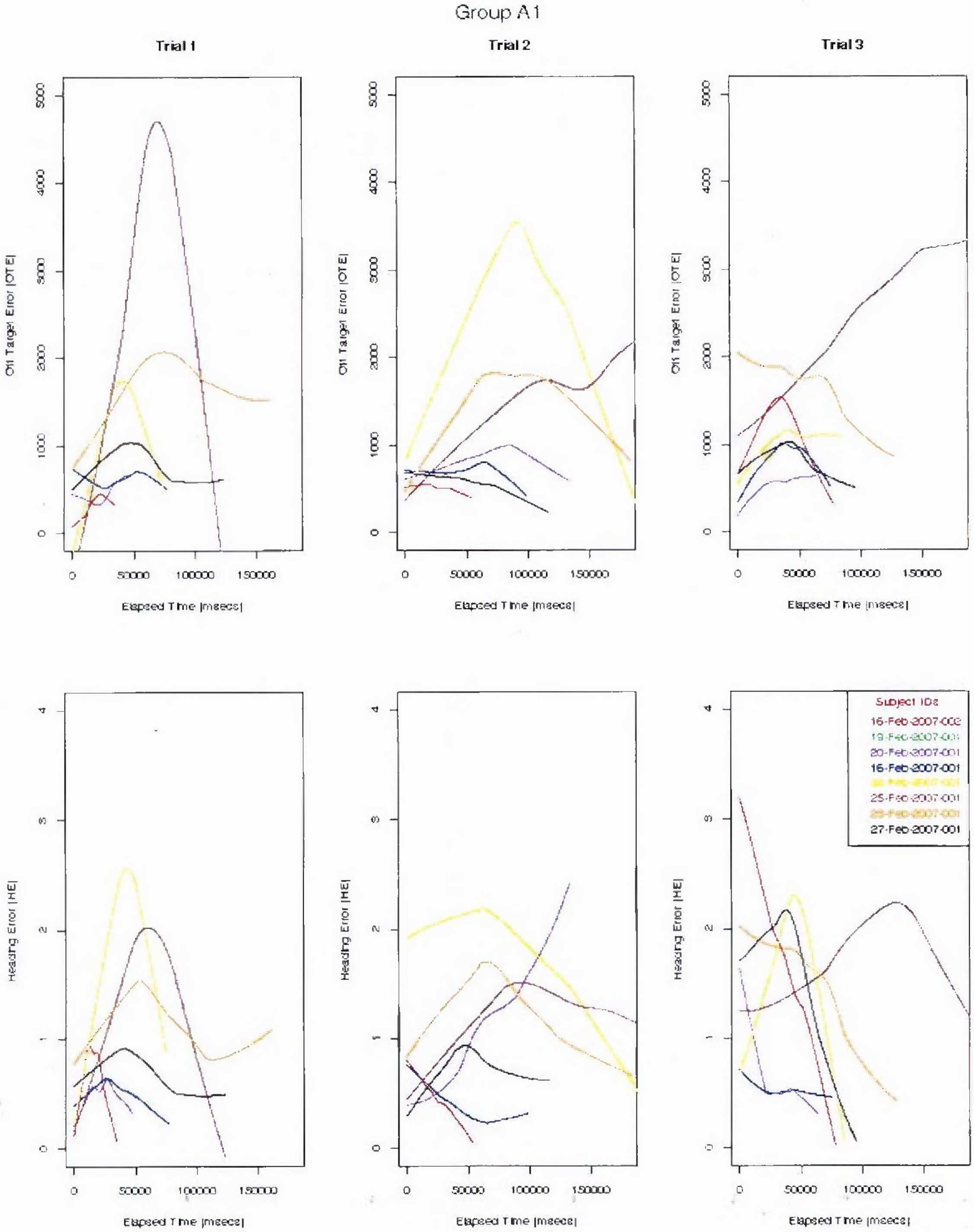


Figure Q.2 OTE and HE trends for all subjects group - A1.

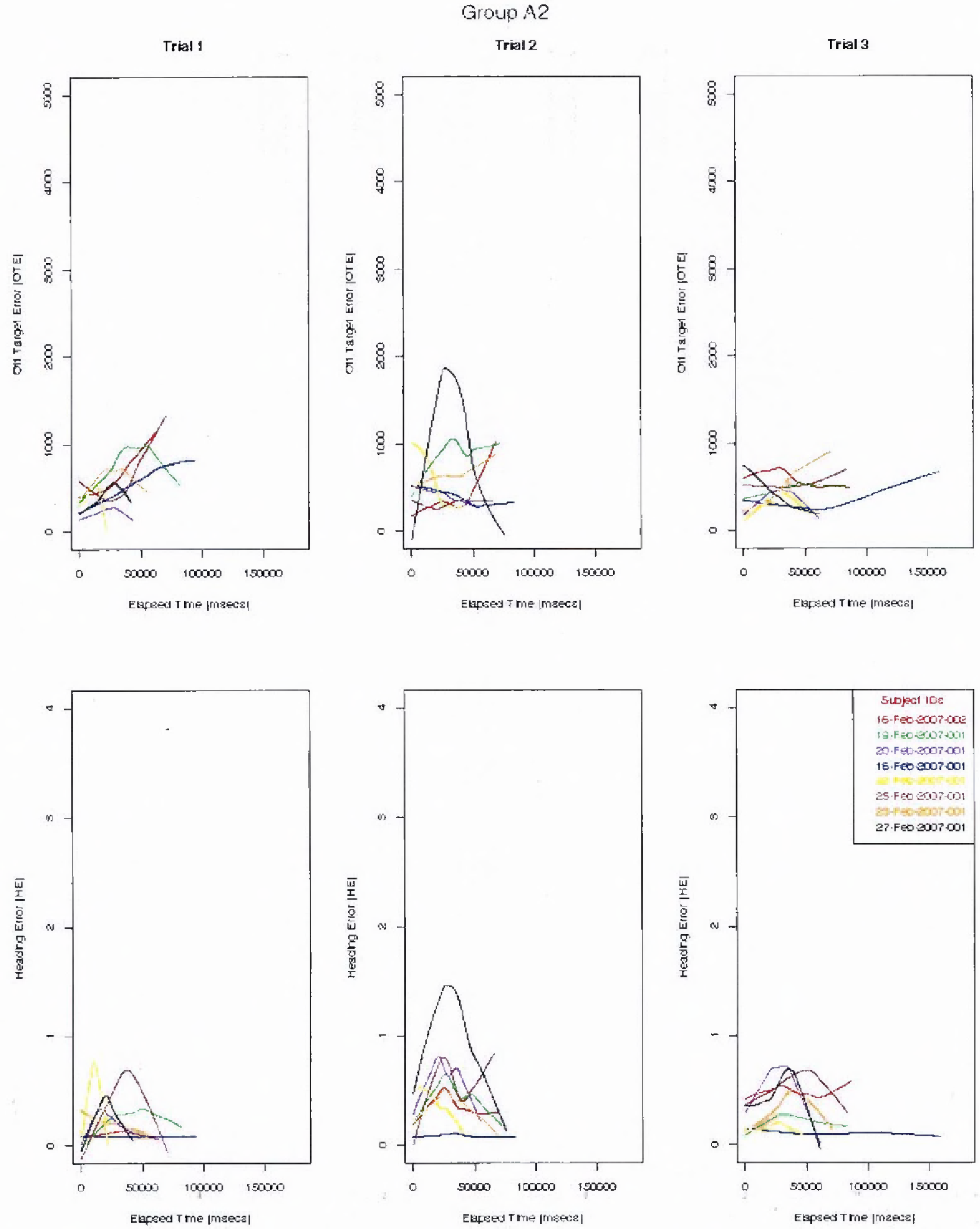


Figure Q.3 OTE and HE trends for all subjects group – A2.

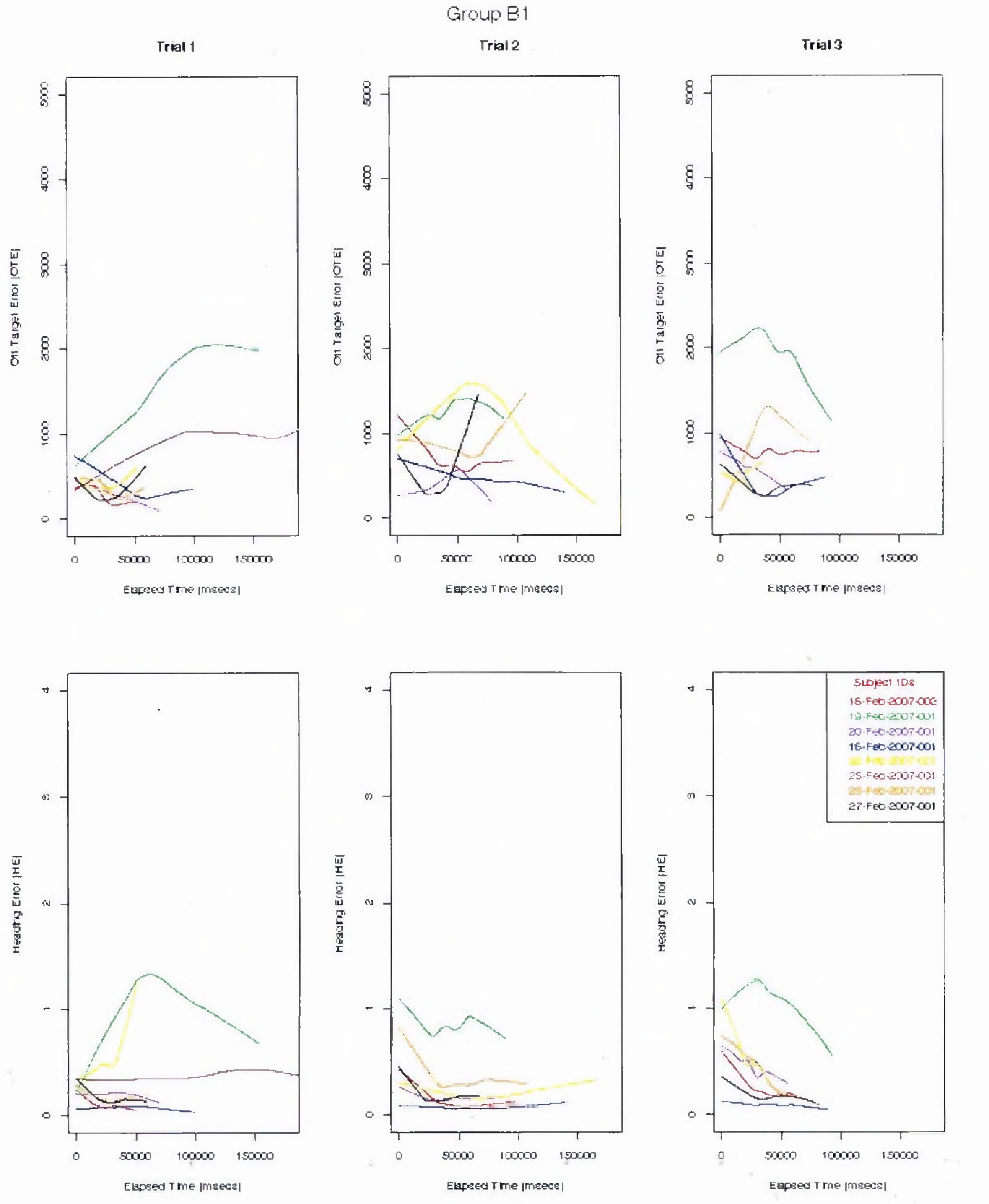


Figure Q.4 OTE and HE trends for all subjects group – B1.

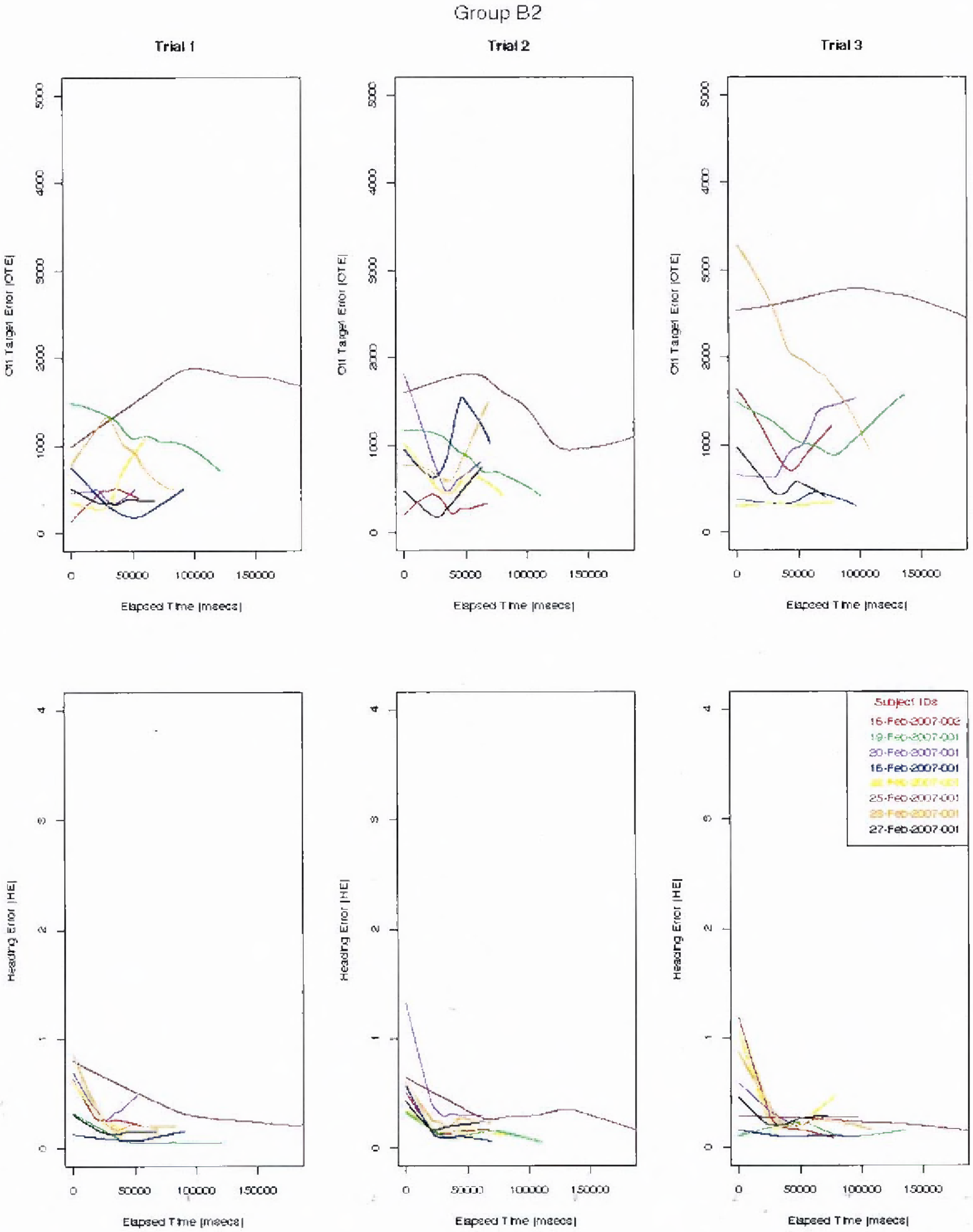


Figure Q.5 OTE and HE trends for all subjects group - B2.

APPENDIX R

SUBJECT TRACKING PLOTS FROM FINAL TEST EXPERIMENT

This appendix contains a compilation of all subjects navigation paths collected during the final experiment.

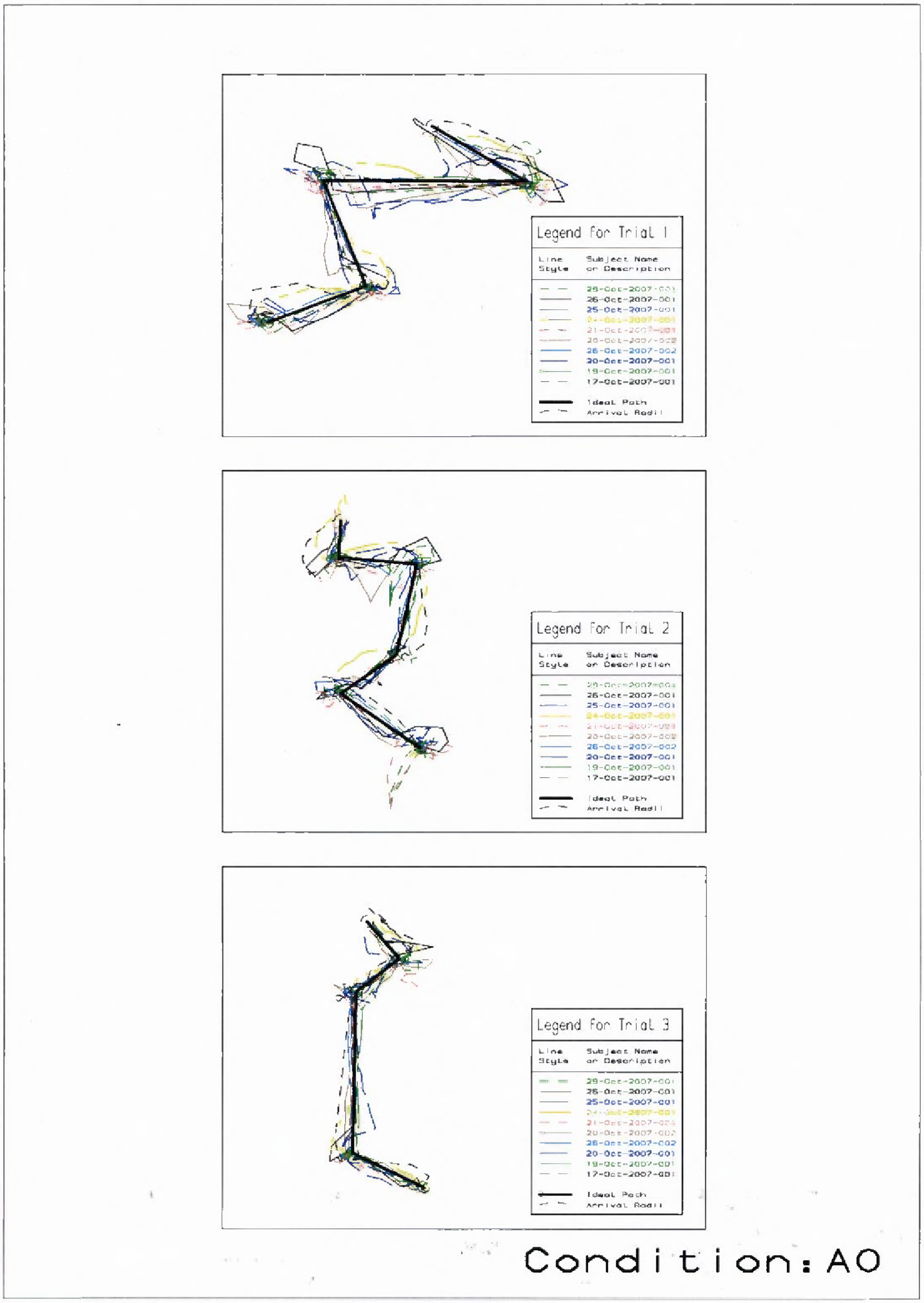


Figure R.1 Subject route data for condition A0.

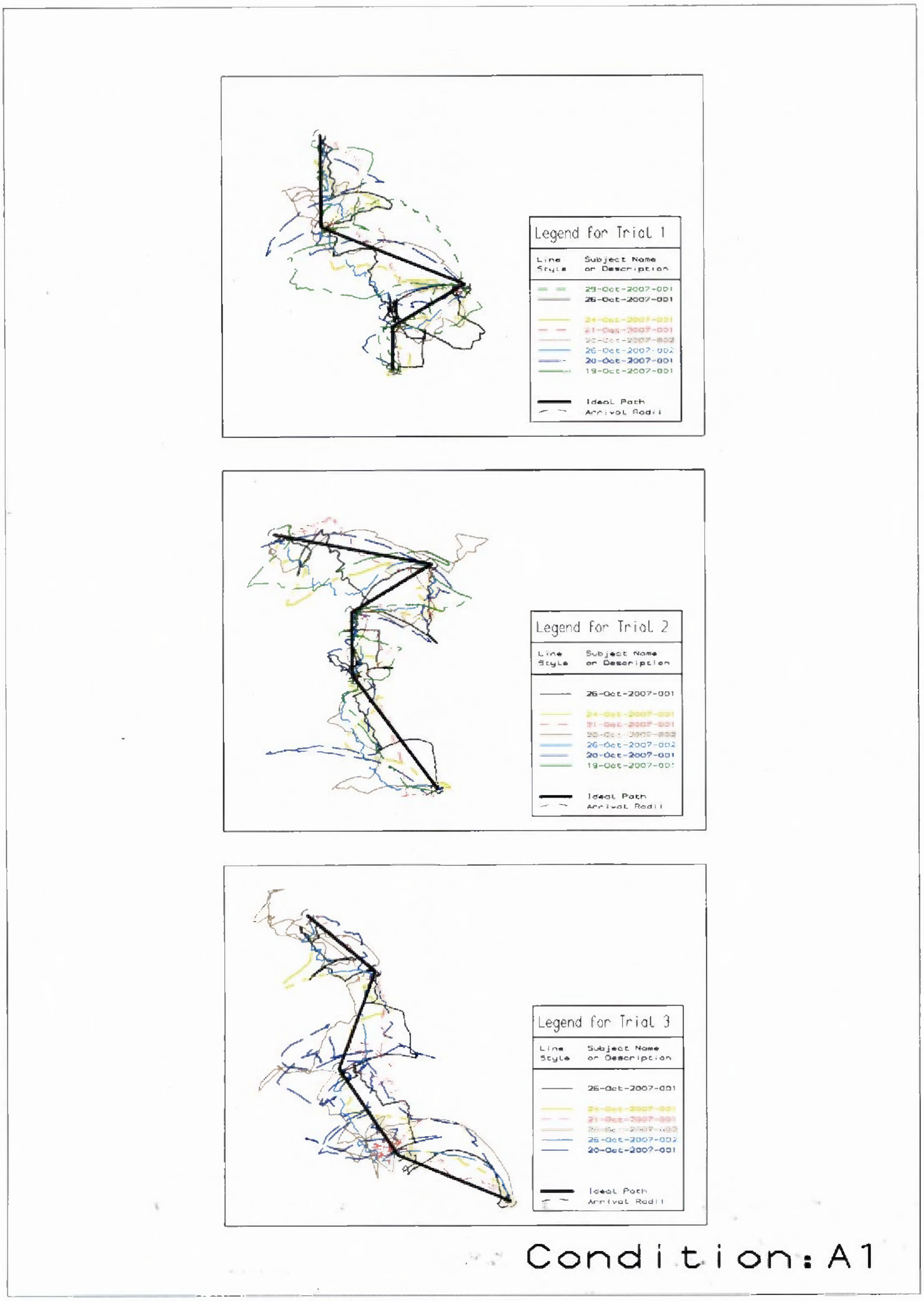


Figure R.2 Subject route data for condition A1.

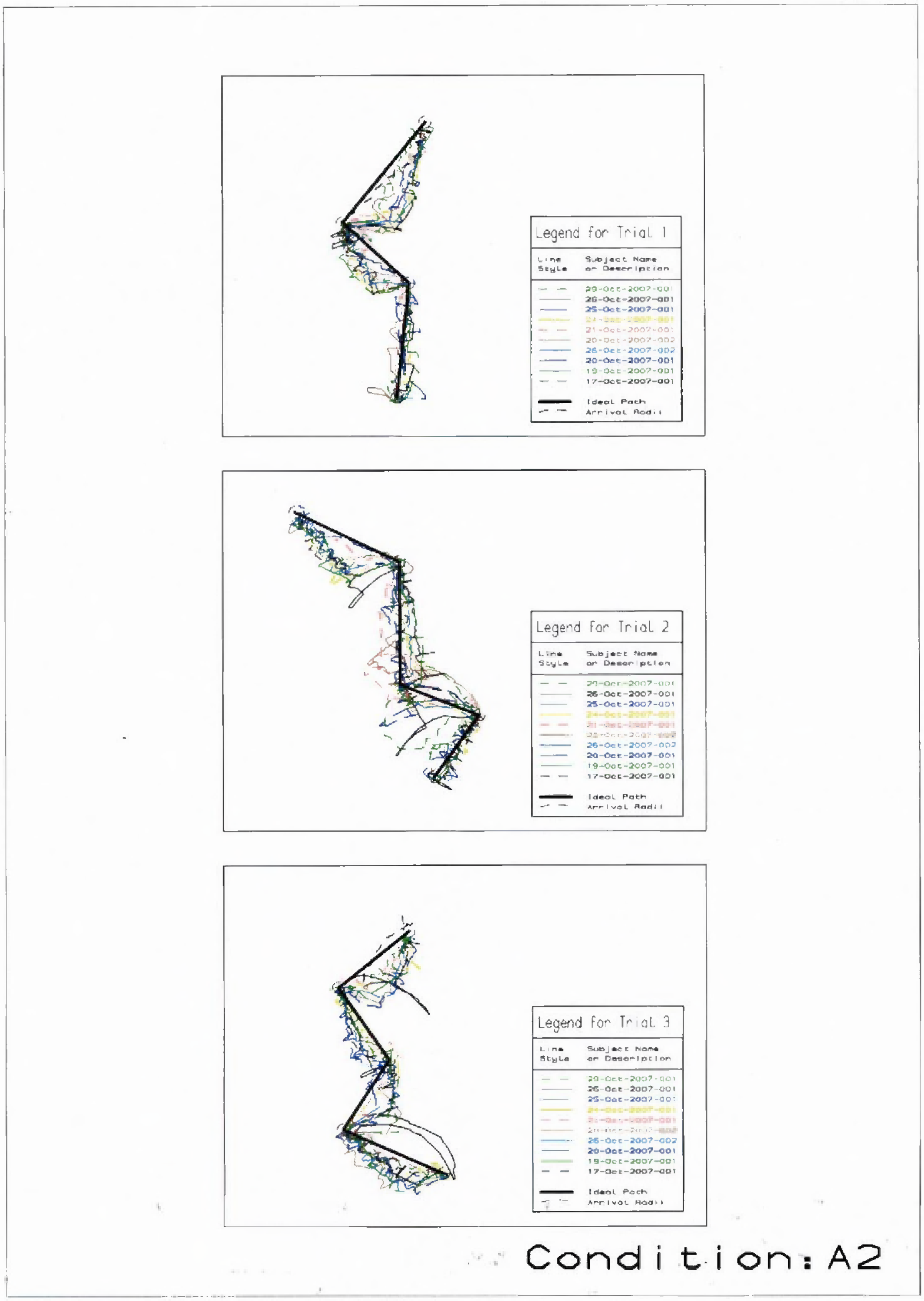


Figure R.3 Subject route data for condition A2.

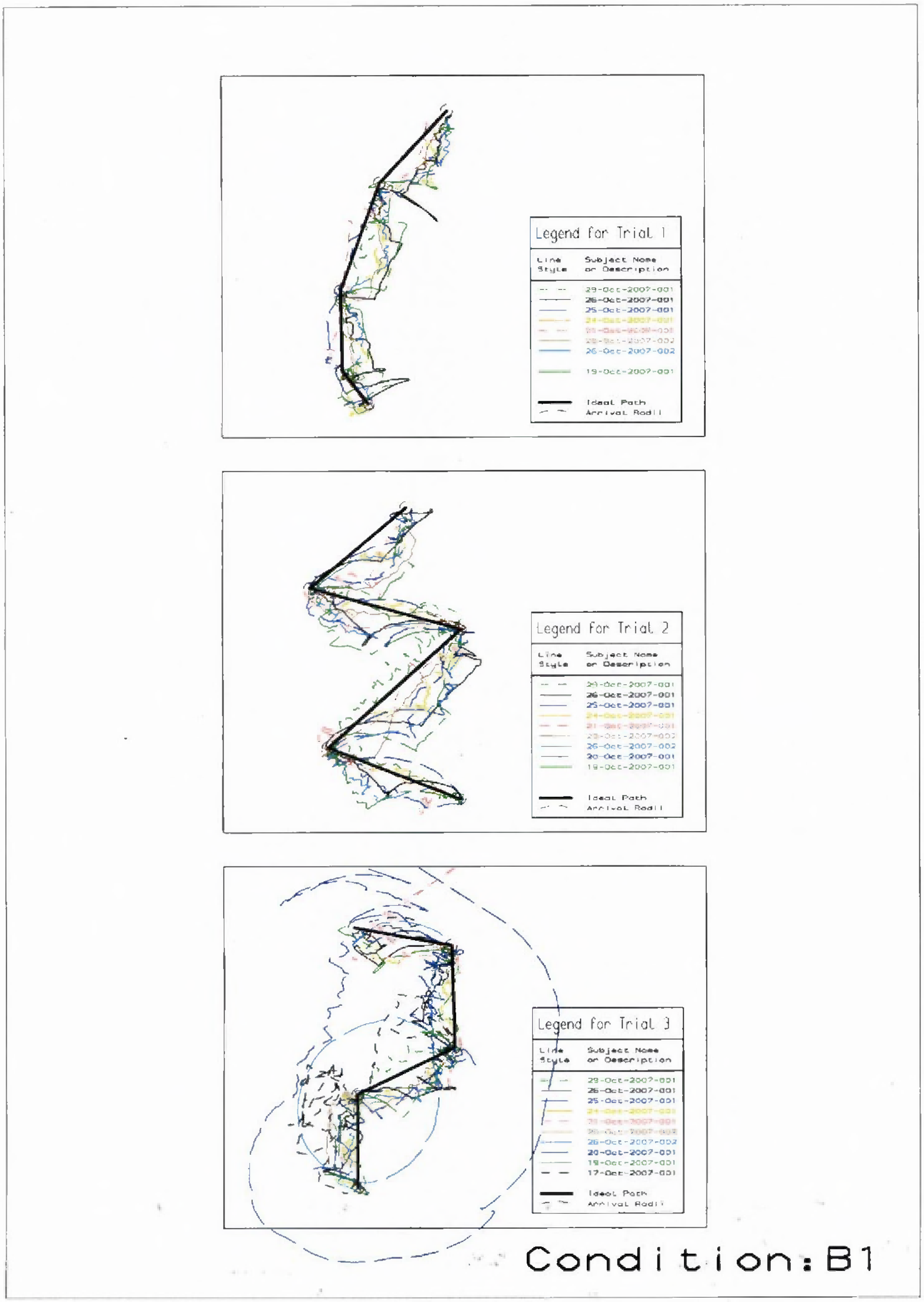


Figure R.4 Subject route data for condition B1.

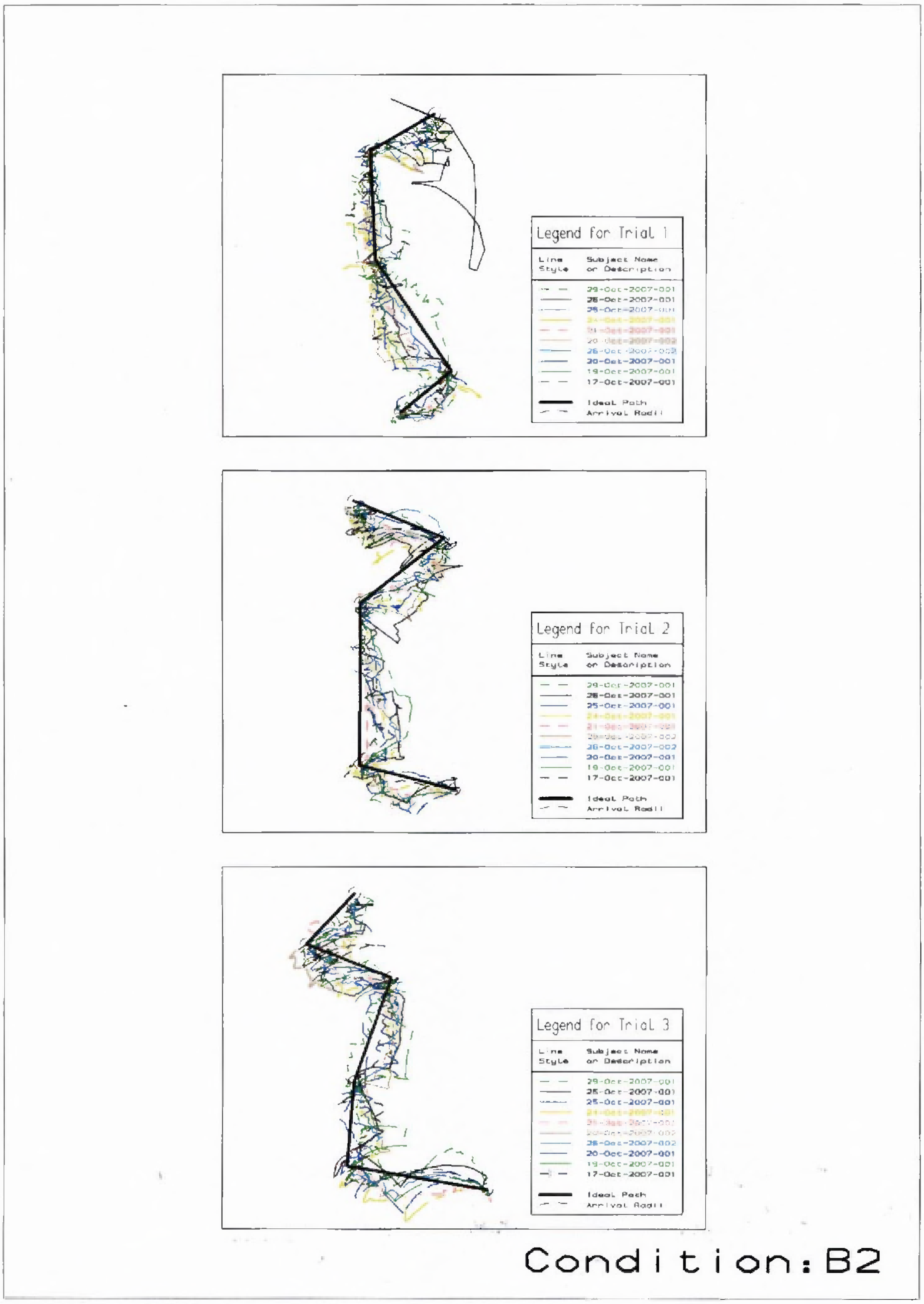


Figure R.5 Subject route data for condition B2.

APPENDIX S

METHOD DESCRIPTION FOR ANALYSIS OF RANK ORDERED SELECTIONS

This appendix contains section two from Quandt's paper titled "Measurement and Inference in Wine Tasting". This section describes the method used for analysis of significance in rank ordered selections (without ties) that was performed in chapters five and seven. This material was extracted verbatim from http://liquidasset.com/corsica.htm and is included here for archival purposes.

2. The Rating of Wines

First of all, we note that there is no cardinal measure by which we can rate wines. Two scales for rating are in common use: (1) the well-known ordinal rank-scale, by which wines are assigned ranks 1, 2, ...,n, and (2) a ``grade"-scale, such as the well-publicized ratings by Robert Parker based on 100 points.[6] The grade scale has some of the aspects of a cardinal scale, in that intervals are interpreted to have meaning, but is not a cardinal scale in the sense in which the measure of weights is one.

Ranking Wines. We shall assume that the are m judges and n wines; hence a table of ranks is an $m\ x\ n$ table and for $m=4$ and $n=3$ might appear as

Table 1. Rank Table for Judges

Judge	Wine ->	A	B	C
Orley		1.	2.	3.
Burt		2.	1.	3.
Frank		1.	3.	2.
Richard		2.	1.	3.
Rank Sums		6.	7.	11.

Notice that no tied ranks appear in the table. The organizer of a wine tasting clearly has a choice of whether tied ranks are or are not permitted. My colleagues' and my preference is not to permit tied ranks, since tied ranks encourage "lazy" tasting; when the sampled wines are relatively similar, the option of using tied ranks enables the tasters to avoid hard choices. Hence, in what follows, no tied ranks will appear (except when wines are graded, rather than ranked). What does the table tell us about the group's preferences? The best summary measure has to be the rank sums for the individual wines, which in the present case turn out to be 6, 7, and 11 respectively. Clearly, wine **A** appears to be valued most highly and wine **C** the least.

The real question is whether one can say that a rank sum is significantly low or significantly high, since even if judges assign rank sums completely at random, we would sometimes find that a wine has a very low (high) rank sum.

Kramer computes upper and lower critical values for the rank sums and asserts that we can test the hypothesis that a wine has a significantly high (low) rank sum by comparing the actual rank sum with the critical values; if the rank sum is greater (lower) than the upper (lower) critical value, the rank sum would be declared significantly high (low).[7] If, in assigning a rank to a particular wine, each of m judges chooses exactly one number out of the set (1, 2, ..., n), the total number of rank patters is n^m and it is easy to determine how many of the possible rank sums are equal to m (the lowest possible rank sum), ..., and nm (the highest possible rank sum). From this is easy to determine critical low and high values such that 5% of the rank sums are lower than the low and 5% are higher than the high critical value.[8] This test is entirely appropriate if one wishes to test {a single rank sum} for significance.

The problem with the test is that typically one would want to make a statement about each and every wine in a tasting; hence one would want to compare the rank sums of all n wines to the critical values; some of the rank sums might be smaller than the small critical value, some might be larger than the larger of the critical values, and others might be in-between. Applying the test to each wine, we would pronounce some of the wines *statistically significantly good* (in the tasters' opinion, some *significantly bad*, and some not significantly good or bad. Unfortunately, this is not a valid use of the test. Consider the experiment of judges assigning ranks to wines one at a time, beginning with wine **A**. Once a judge has assigned a particular rank to that wine, say "1", that rank is no longer available to be assigned by that judge to another wine. Hence, the remaining rank sums can no longer be thought to have been generated from the universe of all possible rank sums, and in fact, the rank sums for the various wines are not independent.

To examine the consequences of applying the Kramer rank sum test to each wine in a tasting, we resorted to Monte Carlo experiments in which we generated 10,000 random rankings of n wines by m judges; for each of the 10,000 replications we counted the number of rank sums that were signficantly high and significantly low, and then classified the replication in a two-way table in which the $(i,j)^{th}$ entry, $(i=0,\ldots,n,$

$j=0,\ldots,n$) indicates the number of replications in which i rank sums were significantly low and j rank sums were significantly high. This experiment was carried out for ($m=4$, $n=4$), ($m=8$, $n=8$) and ($m=8$, $n=12$). The results are shown in Tables 2, 3, and 4.

Table 2. Number of Significant Rank Sums According to Kramer for m=4, n=4.

		j=	
i	0	1	2
0	6414	1221	0
1	1261	1070	16
2	0	12	6

Table 3. Number of Significant Rank Sums According to Kramer for m=8, n=8.

			j=	
i	0	1	2	3
0	4269	1761	93	0
1	1774	1532	211	3
2	97	192	60	0
3	2	3	2	1

Table 4. Number of Significant Rank Sums According to Kramer for m=8, n=12.

		j=			
i	0	1	2	3	4
0	3206	1874	252	4	0
1	1915	1627	357	21	1
2	245	332	121	11	0
3	6	13	12	3	0

Thus, for example, in Table 4, 1,915 out of 10,000 replications had a sole rank sum that was significantly low by the Kramer criterion, 1,627 replications had one rank sum that was signficantly low *and* one rank sum that was significantly high, 357 replications had one significantly low and two significantly high rank sums, and so on. It is clear that the Kramer test classifies way too many rank sums as significant. At the same time, if we apply the Kramer test to a single (randomly chosen) column of the rank table, the 10,00 replications give significantly high and low outcomes as shown in Table 5:

Table 5. Application of Kramer Test to a Single Rank Sum in Each Replication

	Significantly	
(m,n)	High	Low
(4,4)	552	584
(8,8)	507	517
(8,12)	478	467

While the observed rejection frequencies of the null hypothesis of "no significant rank sum" are statistically significantly different from the expected value of 500, using the normal approximation to the binomial distribution, the numbers are, at least, "in the ball-park," while in the case of applying the text to every rank sum in each replication they are not even near.

This suggests that a somewhat different approach is needed to testing the rank sums in a given tasting. Each judge's ranks add up to $n(n+1)/2$ and hence the sum of the rank sums over all judges is $mn(n+1)/2$. Hence, denoting the rank sum for the j^{th} wine by s_j, $j=1,\ldots,n$, we obtain the sum of the rank sums over j as

$$SUM\ s_j=mn(n+1)/2,$$

which, in effect, means that the rank sums for the various wines are located on an $(n-1)$-dimensional simplex. The center point of this simplex has coordinates $m(n+1)/2$ in every direction, and if every wine had this rank sum, there would be no difference at all among the wines. It is plausible that the farther a set of rank sums $s_1,\ldots,s_n$ is located from this center, the more pronounced is the departure of the rankings from the average. However, judging the potential significance of the departure of a single rank sum from the center point has the same problem as the Kramer measure. Therefore we propose to measure the departure of the whole wine tasting from the average point by the (squared) sum of distances of each rank sum from the center points, i.e., by

$$D=SUM(s_j-[m(n+1)/2])^2.$$

In order to determine critical values for D, we resorted to Monte Carlo experiments. Random rank tables were generated for m judges and n wines ($m=4, 5, ..., 12; n=4, 5, ..., 12$), and the D-statistic was computed for each of 10,000 replications; the critical value of D at the 0.05 level was obtained from the sample cumulative distributions. These are displayed in Table 6.

Table 6. Critical values for D at the 0.05 level[9]

	n=								
m	4	5	6	7	8	9	10	11	12
4	50	88	140	216	312	430	570	746	954
5	60	110	180	278	390	550	716	946	1204
6	74	134	218	336	480	664	876	1150	1468
7	88	158	256	394	564	780	1036	1344	1712
8	102	182	300	452	644	894	1174	1534	1984
9	112	206	338	512	732	1014	1342	1742	2236
10	122	230	376	580	820	1128	1500	1954	2508
11	136	252	420	636	902	1236	1642	2140	2740
12	150	276	458	688	992	1360	1836	2358	2998

It is important to keep in mind the correct interpretation of a significant D-value. Such a value no longer singles out a wine as significantly "good" or "bad," but singles out an entire set of wines as representing a significant rank order.

Table 7. Rank Table

Judge	Wine ->	A	B	C	D
Orley		1	2	3	4
Burt		2	1	4	3
Frank		3	1	2	4
Richard		2	1	4	3
Rank Sums		8	5	13	14

The rank sums for the four wines 8, 5, 13, 14, and the Kramer test would say only that wine **D** is significantly bad. In the present example, $D=54$, and the entire rank order is significant; i.e., **B** is significantly better than **A**, which is significantly better than **C**, which is significantly better than **D**.

A final approach to determining the significance of rank sums is to perform the Friedman two-way analysis of variance test.[10] It tests the hypothesis that the ranks assigned to the various wines come from the same population. The test statistic is

$$F=[12/(mn(n+1))]SUM_j s_j^2-3m(n+1)$$

if there are no ties, and is

$$F=\{12SUM_j s_j^2-3m^2n(n+1)^2\}/mn(n+1)+[mn-SUM_i SUM_j^{tau_i} t_{ij}^3/(n-1)]\}$$

if there are ties, where tau_i is the number of sets of tied ranks for judge i (if there are no ties for judge i, then $tau_i=n$) and t_{ij} is the number of items that are tied for judge i in his/her j^{th} group of tied observations (if there are no ties, $t_{ij}=1$). It is easy to verify that the second formula reduces to the first if there are no ties. Critical values for small m and n are given in Siegel and Castellan; for large values F is distributed under the null hypothesis of no differences among the rank sums as $chi^2(n-1)$. It is clear that the Friedman test and the D-test have very similar underlying objectives.

Grading Wines. Grading wines consists of assigning "grades" to each wine, with no restrictions on whether ties are permitted to occur. While the resulting scale is not a cardinal scale, some meaning does attach to the level of the numbers assigned to each wine. Thus, if one a 20-point scale, one judge assigns to three wines the grades 3, 4, 5, while another judge assigns the grades 18, 19, 20,and a third judge assigns 3, 12, 20, they appear to be in complete harmony concerning the *ranking* of wines, but have serious differences of opinion with respect to the absolute quality. I am somewhat sceptical about the value of the information contained in such differences. But we always have the option of translating grades into ranks and then analyzing the ranks with the techniques illustrated above. For this purpose, we reproduce the grades assigned by 11 judges to 10 wines in a famous 1976 tasting of American and French Bordeaux wines.

Table 8. The Wines in the 1976 Tasting

Wine	Name	Final Rank
A	Stag's Leap 1973	1st
B	Ch. Mouton Rothschild 1970	3rd
C	Ch. Montrose 1970	2nd
D	Ch. Haut Brion 1970	4th
E	Ridge Mt.Bello 1971	5th
F	Léoville-las-Cases 1971	7th
G	Heitz Marthas Vineyard 1970	6th
H	Clos du Val 1972	10th
I	Mayacamas 1971	9th
J	Freemark Abbey 1969	8th

Table 9 contains the judges' grades and Table 10 the conversion of those grades into ranks. Since grading permits ties, the ranks into which the grades are converted also have to reflect ties; thus, for example, if the top two wines were to be tied in a judge's estimation, they would both be assigned a rank of 1.5. Also note that grades and ranks are inversely related: the higher a grade, the better the wine, and hence the lower its rank position.

If we apply the critical values as recommended by Kramer, we would find that wines **A**, **B**, and **C** are significantly good (in the opinion of the judges) and wine **H** is significantly bad. The value of the *D*-statistic is 2,637, which is significant for 11 judges and 10 wines according to Table 6, and hence the entire rank order may be considered significant. Computing the Friedman two-way analysis of variance test yields a chi^2 value of 23.93, which is significant at the 1 percent level. Hence, the two tests are entirely compatible and the Friedman test rejects the hypothesis that the medians of the distributions of the rank sums are the same for the different wines.

In this section we compared several ways of evaluating the significance of rank sums. In particular, we argued that the *D*-statistic and the Friedman two-way analysis of variance tests are more appropriate than the Kramer statistic, although for the 1976 tasting they basically agree with one another.

Table 9. The Judges's Grades

	Wine									
Judge	A	B	C	D	E	F	G	H	I	J
Pierre Brejoux	14.0	16.0	12.0	17.0	13.0	10.0	12.0	14.0	5.0	7.0
A. D. Villaine	15.0	14.0	16.0	15.0	9.0	10.0	7.0	5.0	12.0	7.0
Michel Dovaz	10.0	15.0	11.0	12.0	12.0	10.0	11.5	11.0	8.0	15.0
Pat. Gallagher	14.0	15.0	14.0	12.0	16.0	14.0	17.0	13.0	9.0	15.0
Odette Kahn	15.0	12.0	12.0	12.0	7.0	12.0	2.0	2.0	13.0	5.0
Ch. Millau	16.0	16.0	17.0	13.5	7.0	11.0	8.0	9.0	9.5	9.0
Raymond Oliver	14.0	12.0	14.0	10.0	12.0	12.0	10.0	10.0	14.0	8.0
Steven Spurrier	14.0	14.0	14.0	8.0	14.0	12.0	13.0	11.0	9.0	13.0
Pierre Tari	13.0	11.0	14.0	14.0	17.0	12.0	15.0	13.0	12.0	14.0
Ch. Vanneque	16.5	16.0	11.0	17.0	15.5	8.0	10.0	16.5	3.0	6.0
J.C. Vrinat	14.0	14.0	15.0	15.0	11.0	12.0	9.0	7.0	13.0	7.0

Table 10. Conversion of Grades into Ranks

	Wine									
Judge	A	B	C	D	E	F	G	H	I	J
Pierre Brejoux	3.5	2.0	6.5	1.0	5.0	8.0	6.5	3.5	10.0	9.0
A. D. Villaine	2.5	4.0	1.0	2.5	7.0	6.0	8.5	10.0	5.0	8.5
Michel Dovaz	8.5	1.5	6.5	3.5	3.5	8.5	5.0	6.5	10.0	1.5
Pat. Gallagher	6.0	3.5	6.0	9.0	2.0	6.0	1.0	8.0	10.0	3.5
Odette Kahn	1.0	4.5	4.5	4.5	7.0	4.5	9.5	9.5	2.0	8.0
Ch. Millau	2.5	2.5	1.0	4.0	10.0	5.0	9.0	7.5	6.0	7.5
Raymond Oliver	2.0	5.0	2.0	8.0	5.0	5.0	8.0	8.0	2.0	10.0
Stev. Spurrier	2.5	2.5	2.5	10.0	2.5	7.0	5.5	8.0	9.0	5.5
Pierre Tari	6.5	10.0	4.0	4.0	1.0	8.5	2.0	6.5	8.5	4.0
Ch. Vanneque	2.5	4.0	6.0	1.0	5.0	8.0	7.0	2.5	10.0	9.0
J.C. Vrinat	3.5	3.5	1.5	1.5	7.0	6.0	8.0	9.5	5.0	9.5
Rank Totals	41.0	43.0	41.5	49.0	55.0	72.5	70.0	79.5	77.5	76.0
Group Ranking	1	3	2	4	5	7	6	10	9	8

REFERENCES

Accessworld News. (May 2000). Retrieved January 10, 2006, from http://www.afb.org/afbpress/pub.asp?DocID=AW0103news

Agrawala, M., & Stolte, C. (2001). Rendering effective route maps: Improving usability through generalization. *Proceedings of the 28th Annual Conference on Computer Graphics and Interactive Techniques*, 241-249.

Alty, J. L. & Rigas, D. I. (1998). Communicating graphical information to blind users using music: The role of context. *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*. 574-581.

Amento, B, Hill, W., & Terveen L. (2002). The sound of one hand: A wrist-mounted bio-acoustic fingertip gesture interface. *Conference on Human Factors in Computing Systems*. 724-725.

Arditi, A., Holmes, E., Reedijk, P., & Whitehouse, R. (1999). Interactive tactile maps, visual disability, and accessibility of building interiors. *Visual Impairment Research*, *1*(1), 11-19.

Arthur, P. & Passini, R. (1992). *Wayfinding: People, signs and architecture*, Toronto: McGraw Hill Companies.

Azuma, R, (1997). A survey of augmented reality. *Presence: Teleoperators and Virtual Environments*, *6*(4), 355-385.

Blattner, M. M., Sunikawa, D. A., & Greenberg R. M. (1989). Earcons and icons, their structure and common design principles. *Human Computer Interaction*, *4*(1), 11-44.

Blasch, B., Wiener, W., & Welsh R. (1997). *Foundations of orientation and mobility* (2nd Edition). New York, NY: American Foundation for the Blind.

Barlow, J. M., Bentzen, B. L., & Taboe, L. S. (2003, May). Accessible pedestrian signals: Synthesis and guide to best practice, Retrieved January 10, 2006, from http://trb.org/publications/nchrp/nchrp_rrd_278.pdf

Bertelsen, O.W., & Nielsen C. (2000). Augmented reality as a design tool for mobile interfaces. *Proceedings of the Conference on Designing Interactive Systems Processes, Practices, Methods and Techniques*, 185-192.

Brown, W. J., Malveau, R. C., & Mowbray, T. J. (2001). *Antipatterns: Refactoring software, architectures, and projects in crisis*. New York, NY: Wiley.

Carpman, J., & Grant, M. (2006). *Directional Sense*. Evans & Co.

Chan, M. C., & Ramjee R. (2005). TCP/IP performance over 3G wireless links with rate and delay variation. *Wireless Networks*, *11*(1-2), 81-97.

Chen, X.C., Tremaine, M., Chun, J., Lutz, R.J., Lacsina, P.O. (2006). AudioBrowser: A mobile browsable information access for the visually impaired, *Universal Access in the Information Society*, *5*(1), 4-22.

Donker, H., Klante P., & Gorny P. (2002, October). The design of auditory user interfaces for blind users, presented at NordiCHI, Retrieved January 10, 2006, from http://www-cg-hci-informatik,uni-oldenberg.de/resources/zib_nordichi.pdf

Dowie, A.T. (1988). *Management and practice of low vision acuity.* London: The Eastern Press.

Downes, L. & Mui, C. (1998). *Unleashing the killer app: Digital strategies for market dominance*, Cambridge, MA: Harvard Business School Press.

Fitzmaurice, G., & Buxton, B. (1997). An empirical evaluation of graspable user interfaces: Towards specialized, space-multiplexed input. *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*, 43-50.

Friedlander, N., Schlueter, K., & Mantei, M. (1998). Bulls eye! When Fitt's Law doesn't fit in. *ACM CHI*, Los Angeles CA. ACM Press, Addidson Wesley, 257-264.

Fruchterman, J. R. (1998, August). Written [Congressional] testimony of James R. Fruchterman, President, Arkenstone, Inc., On developing partnerships for assistive and universally designed technology for persons with disabilities. Retrieved May 10, 2006, from http://www.house.gov/science/fruchterman_08-04.htm

Gamma, E., Helm, R, Johnson R., & Vlissides, J. (1995). *Design patterns: Elements of reusable object-oriented software.* Addison-Wesley Professional Computing Series.

Gaver, W. W. (1986). Auditory icons: Using sound in computer interfaces. *Human Computer Interaction*, 2, 167-177.

Gaver, W. W. (1989). The SonicFinder, a prototype interface that uses auditory icons. *Human Computer Interaction*, *4*, 67-94.

Gaver, W. W. (1994). Using and creating auditory icons. *Auditory Display: Sonification, Audification and Auditory Interfaces*, edited by G. Kramer, SFI Studies in the Sciences of Complexity Proc. Vol. XVIII, Addison-Wesley, 417-446.

Haber, L., Haber, R.N., Penningroth, S., Novak, K., & Radgowski, H. (1993). Comparisons of nine methods of indicating the direction to objects: Data from blind adults. *Perception, 22*(1), 35-47.

Hankinson, J. C. K., & Edwards, A.D.N. (1999). Designing earcons with musical grammars, *ACM SIGCAPH Computer and the Physically Handicapped, 65*, 16–20.

Heathcote, C. (2004). 35 ways to track your location, presented at O'Reilly Emerging Technologies Conference '04. Retrieved May 10, 2006, from http://conferences.oreillynet.com/cs/et2004/view/e_sess/4657

Holmes, E., Jansson, G., & Olson, E. (1996). Tactile enhancement of the reading of a digital map presented via synthetic speech._*Needs, Solutions, Developments: Proceedings of the Fifth International Conference on Maps and Diagrams for Visually Impaired People.* Ljublijana, Slovenia.

Holmes, E., & Jansson, G. (1997). A touch tablet enhanced with synthetic speech as a display for blind people's reading of virtual maps._*Technology and Persons with Disabilities: Proceedings of the Twelfth Annual International Conference on Technology for People with Disabilities.* Northridge, CA.

Holmes, E., & Arditi, A. (1997). Tactile maps of building interiors for blind persons: Architectural vs. path information for route planning._New York: Arlene R. Gordon Research Institute, The Lighthouse Inc. (Technical Report).

Holmes, E., & Arditi, A. (1998). Wall vs. path tactile maps for route planning in buildings. *Journal of Visual Impairment & Blindness, 92,* 531-534.

Holmes, E., & Arditi, A. (1999). *Feasibility of an interactive tactile map system for indoor wayfinding. International Conference on Low Vision.*_ Swets and Zeitlinger.

Hightower J. & Borriello G. (2001, August). Location systems for ubiquitous computing, *Computer*, *34*(8), 57-66. IEEE Computer Society Press.

Humanware Trekker Product Website, retrieved November 11, 2005, from http://www.humanware.ca/web/en/p_DA_Trekker.asp

Jacko, J. A., Vitense, H. S., & Scott, I. U. (2002). Perceptual impairments and computing technologies. In J. A. Jacko and A. Sears (Eds.), *The Human-Computer Interaction Handbook: Fundamentals, Evolving Technologies and Emerging Applications* . 502-504. Mahwah, NJ: Lawrence Erlbaum Associates, Inc.

Kennel, A.R. (1996). Audiograf: A diagram reader for the blind. *Proceedings on the Second Annual ACM Conference on Assistive Technologies*, Vancouver, Canada, 51-56.

Kramer, G., Walker, B., Bonebright, T., Cook, P., Flowers, J., Miner, N. & Neuhoff, J. (1997). Sonification report: Status of the field and research agenda, Retrieved May 27, 2007, from http://www.icad.org/websiteV2.0/References/nsf.html

Krutchen, P., (1995). Architectural blueprints – the "4+1" view model of software architecture, *IEEE Software 12(6)*, 42-50.

Kupfer, C. (2000). The National Eye Institute's low vision education program: Improving quality of life. *Ophthalmology*, *107*, 229-230.

LaPlante, M.P. (1988). Prevalence of conditions causing need for assistance in activities of daily living. In M.P. LaPlante (Ed.), *Data on Disability from the National Health Interview Survey*, 1983-1985. Washington, DC: National Institute on Disability and Rehabilitation Research.

Leonard, R. (2002). Statistics on vision impairment: A resource manual. Arlene R. Gordon Research Institute, Lighthouse International, 5th Edition. Retrieved May 10, 2006, from http://www.lighthouse.org/downloads/researchstats.pdf

Loomis, J.M. (2003). Sensory replacement and sensory substitution: Overview and prospects for the future. *Converging Technologies for Improving Human Performance: Nanotechnology, Biotechnology, Information Technology and Cognitive Science*, in M.C. Roco and W.S. Bainbridge (Eds.), Kluwer Academic Publishers.

Loomis, J. M., Klatzky, R. L, & Golledge, R. G. (1998). Navigation system for the blind, auditory display modes and guidance. *Presence, Teleoperators and Virtual Environments*, *7*, 193-203.

Loomis, J.M., Golledge, R.G., Klatzky, R.L., Speigle, J., & Tietz, J. (1994). Personal guidance system for the visually impaired. *Proceedings of the First Annual ACM /SIGCAPH Conference on Assistive Technologies*, Marina Del Ray, California, October 31-November 1, 85-90.

Lynch, K. (1960). *The image of the city*. MIT Press.

Mansur, D.L., Blattner, M.M., & Joy, K.I. (1985). Sounds-Graphs: A numerical data analysis method for the blind. *Journal of Medical Systems*, *9*(3), 163-174.

Marston, J.R., Loomis, J.M., Klatzky, R.L., Golledge, R.G., & Smith, E.L. (2006). Evaluation of spatial displays for navigation without sight. *ACM Transactions on Applied Perception*, *3*(2), 110-124.

McCabe, M.R. (n.d.). Evaluation of a low vision navigation aid, NavAid, in a virtual environment, Retrieved May 11, 2006, from http://psych.mrmccabe.com/documents/navaid_final_proposal.pdf

McGookin, D. K. & Brewster S.A. (2004, October). Understanding concurrent earcons: Applying auditory scene analysis principles to concurrent earcon recognition. *ACM Transactions on Applied Transactions*, *1*(2), 130-155.

McQueen, J.C. (1995). Auditory pie menus. Masters Thesis, University of Toronto, Toronto, CA.

Mehr, E.B. (1975). *Low Vision Care.* Chicago: Professional Press.

Miles, R. & Hamilton, K. (2006). *Learning UML 2.0.* O'Reilly Media, Inc.

Mitsubishi Electric Research Laboratory website, Retrieved May 27, 2007, from http://www.merl.com/projects/DiamondTouch

The MoBIC Project website. Retrieved November 11, 2005, from http://phoenix.herts.ac.uk/SDRU/MOBIC/mobic.html

Morville, P. (2005). *Ambient findability.* Sebastopol, CA: O'Reilly and Associates.

Multi-touchscreen project website, Retrieved May 27, 2007, from http://multi-touchscreen.com

Mynatt, E. D., Weber, G. (1994) Non-visual presentation of graphical user interfaces, contrasting two approaches. *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems: Celebrating Interdependence.* 166-172.

National Advisory Eye Council. (1993). *Vision research: A national plan* 1994-1998. Bethesda, MD: National Eye Institute, National Institute of Health.

Nelson, K.A. (1987). Visual impairment among elderly Americans: Statistics in transition. *Journal of Visual Impairment and Blindness*, *81*, 331-334.

Nelson, K., & Dimitrova, G. (1993). Statistical brief #36: "Severe visual impairment" in the U.S. and the states. *Journal of Visual Impairment and Blindness*, *87*, 80-85.

Ogata, T., Makino, H., Ishii I., & Nakashizuka, M. (1997). Location guidance system for the visually impaired using an invisible bar code. *Transactions of IEICE*, J80/D-2, 3101–3107 (in Japanese).

Petrie, H., Morley S., & Weber G. (1995). Tactile based direct Mmanipulation in GUIs for blind users. *Proceedings of ACM CHI'95 Conference on Human Factors in Computing Systems*, 2, 428-429.

Pitt, I., & Edwards, A. D. N. (1996). Improving the usability of speech based interfaces for blind users. *Proceedings of the Second Annual ACM Conference on Assistive Technologies*, Vancouver, British Columbia. Canada: ACM Press.

Priyantha, N.B., Chakraborty A., & Balakrishnan, H. (2000). The Cricket location support system. *Proceedings of the Sixth Annual International Conference on Mobile Computing and Networking.* Boston, Massachusetts, 32-43.

Ramloll R. & Brewster S. (2002). A generic approach for augmenting tactile diagrams with spatial non-speech audio sounds, *Conference on Human Factors in Computing Systems,* Minneapolis, MN, 770-771.

Rosenfeld, R., Olsen D., & Rudnickey A. (2001, November/December). Universal speech interfaces, *ACM Interactions.*

Ross, D. A., & Lightman, A. (2005). Talking braille: A wireless ubiquitous computing network for orientation and wayfinding. *Proceedings of the 7th International ACM SIGACCESS Conference on Computers and Accessibility,* Baltimore, Maryland, 98-105.

Ross, D. A., & Blasch, B. B. (2000). Evaluation of orientation interfaces for wearable computers. *Fourth International Symposium on Wearable Computers.* 51.

Ross, D. A., & Blasch B. B. (2000). Wearable interfaces for orientation and wayfinding, *Proceedings of the Fourth International ACM Conference on Assistive Technologies*, Arlington Virginia, 193-200.

Rosenthal, R., & Rosnow, R.L. (1991). *Essentials of Behavioral Research*, Second Edition, McGraw Hill.

Sandor, C. & Klinker, G. (2005). A rapid prototyping software infrastructure for user interfaces in ubiquitous augmented reality, *Journal for Personal and Ubiquitous Computing, 9*, 169-185. Springer Verlag.

Scaletti, C. (1994). Sound synthesis algorithms for auditory data representations. In G. Kramer, (Ed.), *Auditory Display: Sonification, Audification and Auditory Interfaces*, 223-251. Reading, MA: Addison Wesley.

Schneiderman, B. (1992). *Designing the User Interface, Strategies for Effective Human Computer Interaction* (3rd Edition). Addison Wesley.

Sendero Product Video, Retrieved May 8, 2006, from http://www.senderogroup.com/gps.wmv

Stafford T., & Webb M. (2004). *Mind Hacks: Tips & Tricks for Using Your Brain.* O'Reilly Media, Inc.

Strong, J.G., Pace, R.J., & Plotkin A.D. (1988). Low vision services: A model for sequential intervention and rehabilitation. *Canadian Journal of Public Health, 79*, 50-54.

Strothotte, T., Fritz S., Ranier M., Radd, A., Petrie, H., Johnson V., Reichart, L., & Schalt, A. (1996). Development and dialogue systems for a mobility aid for blind people: Initial design and usability testing. *Proceedings of the Second Annual ACM Conference on Assistive Technologies*, Vancouver, B.C., 138-144.

Smith, A.C., Francioni, J. M., Anwar, M., Cook, J. S., Hossain A., & Rahman, M. (2004). Nonvisual tool for navigating the hierarchical structure of programs. *Proceedings of Assets2004*, Atlanta, GA, 133-139.

Todman, J.B., Dugard, P. (2001). *Single-case and Small-n Experimental Designs: A Practical Guide To Randomization Tests.* Lawrence Erlbaum.

Tolman, E. C. (1948). Cognitive Maps in Rats and Men. *The Psychological Review*, *55*(4), 189-208.

UCSB Personal Guidance System (PGS) website, Retrieved January 11, 2006, from http://www.geog.ucsb.edu/pgs/main.htm

UmlAsSketch website, Retrieved may 27, 2007, from http://www.martinfowler.com/bliki/UmlAsSketch.html

Vogel, S. Dog+: A PDA based navigation system for the blind (master's thesis), Retrieved January 11, 2006, from http://www.cs.unc.edu/~vogel/IP/

Walker, B., Lindsay J., & Godfrey J. (2003). The audio abacus, representing numerical values with nonspeech sound for the visually impaired. *Proceedings of the 6th International ACM SIGACCESS Conference on Computers and Accessibility*, Atlanta GA, 9-15.

Walker, B., & Lindsay, J. (2006). Navigation performance with a virtual audio display: Effects of beacon sound, capture radius and practice. *Human Factors*, *48*(2), Human Factors and Ergonomics Society.

Zhao, H., Plasant C., Schneiderman B., & Duraiswami R. (2004). Sonification of geo-referenced data for auditory information seeking: Design principles and pilot study. *Proceedings of ICAD 04-Tenth Meeting of the International Conference on Auditory Display,* Sydney, Australia.

Zhao, H., Smith, B., Norman, K., Plaisant, C., & Schneiderman, B. (2004). Listening to maps: User evaluation of interactive sonifications of geo-referenced data. Submitted to *IEEE Multimedia Special Issue on Interactive Sonification*, Technical Report HCIL-2004-23, University of Maryland.