Virtual Reality-based Investigation of Four Cognitive Theories for Navigation

by

Carolyn Ann Bussi

Dissertation submitted to the Faculty of the
Virginia Polytechnic Institute and State University
in partial fulfillment of the requirements for the degree of
Doctor of Philosophy
in
Industrial and Systems Engineering

APPROVED:

Jeffrey C. Woldstad

John G. Casali

Sherry P. Casali

C. Patrick Koelling

Robert C. Williges

November 1995
Blacksburg, Virginia

Key Words: Cognitive Theory, Navigation, Virtual Reality

VIRTUAL REALITY-BASED INVESTIGATION
OF FOUR COGNITIVE THEORIES
FOR NAVIGATION

by

Carolyn Ann Bussi

Committee Co-chairs: Jeffrey C. Woldstad and John G. Casali
Industrial and Systems Engineering

(ABSTRACT)

Intelligent Transportation Systems (ITS) refer to an integrated group of technologies which can improve safety, reduce congestion, enhance mobility, minimize environmental impact, save energy, and promote economic productivity in our transportation system. A driver-centered design philosophy will promote these benefits. These advanced technologies will thereby enhance the safety and efficiency of automobile transportation. This research dealt with In-vehicle Routing and Navigational Systems (IRANS). IRANS provide drivers with information about how to get from one place to another, information on traffic conditions, and recurrent and non-recurrent urban traffic congestion.

The problem studied in this research was whether performance on navigation tasks can be predicted by cognitive theories (Multiple Resource Theory, Stimulus-Central Processing-Response Compatibility Theory, Recoding Mechanism Theory, and Dual Coding Theory). A secondary problem was the determination of the relationship between navigation and spatial ability. Spatial ability has been linked to map reading performance. Issues addressed included

display modalities and information processing codes. The effect of different display modalities on driver performance and workload was the first issue. The different display methods investigated were visual systems (current dashboard mounted display types) and auditory systems (computer generated voice communication systems). The second issue was the effect of different information processing codes on driver performance and workload. The information processing code determines the method used to present information to the driver using the display; in this research both verbal and spatial codes were considered. Verbally coded information consists of a series of sequential directions (for example, "go to the next street and turn right"), while spatially coded information is presented using a map display for visual systems.

The results indicate that the best cognitive theory for predicting navigational behavior is the dual coding theory. Subjects not only performed better, but also preferred navigational aids where the navigational information was presented in more than one way. This indicates that designers and engineers should develop navigational aid displays to incorporate redundant navigational information. Some differences for navigational performance were shown for high versus low spatial ability subjects, but the subjective measures of workload and preference did not show any differences.

Dedicated to my parents, Joseph Frank and Jean Ann Bussi

ACKNOWLEDGMENTS

This research was supported by an Intelligent Vehicle Highway System Research Center of Excellence award from the Center for Transportation Research at Virginia Tech sponsored by the Federal Highway Administration. Dr. Jeffrey C. Woldstad served as principal investigator. A Research Infrastructure Grant from the National Science Foundation purchased the Superscape VRT™ virtual reality software package used to program the environment for this study.

I would like to extend my deepest gratitude and thanks to Dr. Jeffrey C. Woldstad who served as my major advisor and mentor throughout the duration of Ph.D. degree and dissertation research. He was an invaluable source of guidance and encouragement during my years at Virginia Polytechnic Institute and State University and a great friend.

I would also like to thank Dr. John C. Casali (who graciously served as co-chair following Dr. Woldstad's departure from the university), Dr. Sherry P. Casali, Dr. C. Patrick Koelling, and Dr. Robert C. Williges who served on my committee during my dissertation research. They were an inspiration to me as well as extremely helpful in assisting me in all stages of my dissertation work.

Many thanks must be given to Yaron Rachlin for his assistance in troubleshooting, his programming ability, and his commitment to everything he does. I would also like to thank Steve Belz for his assistance in recruiting participants and running the experiment. Additional thanks to John Lindal at the California Institute of Technology for the use of his random maze generator for the creation of the mazes used in this research. I would also like to thank John

Deighan and Will Vest for talking with me about the more technical aspects of this research.

Thank you to all of my friends who have given me encouragement throughout the duration of my graduate study. Special thanks go to Shane Evans and Suzie Lee whose friendship has made my time here enjoyable and whose support has helped me through the rougher times.

Finally, my deepest thanks and love go to Mom, Dad, Doreen, Tim and Paul who always gave (and still continue to give) me the support and encouragement that I needed to finish this and throughout all of my years.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF APPENDICES

I. INTRODUCTION

Overview

The aim of this research was to investigate different methods to present drivers with navigation information. With the passage of the Intermodal Surface Transportation Efficiency Act of 1991, the development of Intelligent Transportation System (ITS) components, including Automated Traveler Information Systems (ATIS), has been deemed a priority in order to address the nation's transportation problems. The need for attention to human factors issues in ITS was specifically mentioned in this legislation (Perez and Mast, 1992). "The design of navigational devices must be guided by human factors considerations to reduce unsafe operations. Although an on-board unit may aid drivers in a given task, its operation may also introduce significant hazards" (Walker, Alicandri, Sedney, and Roberts, 1991). Rather than allowing technology to dictate what information a driver must deal with, the technology can be shaped to provide the kind of information a driver needs in an effective format; this is considered user-centered design (Owens, Helmers, and Sivak, 1993). It is important to use the flexibility of vehicle electronic systems and displays to lighten the information processing load of the driver (Fowkes, 1984). Research must continue to search for the best way to present navigational information to the driver (Antin, 1993). Some of the issues to be addressed are: 1) weighing the relative merits of visual-spatial versus auditory-verbal information presentation methods; 2) if a map is used, should it be heading-up, north-up, or some combination of both; and 3) is the head-up display format suitable for complex navigational information. This research attempted to answer some of these issues.

The problems studied in this research were:

1. Can information processing theories predict performance on navigation tasks?
2. What is the relationship between navigation and spatial ability?

Issues addressed included display modalities and information processing codes. The effect of different display modalities on driver performance and workload was the first issue. According to Ross, Vaughan, and Nicolle (1994) no guidelines exist for the best mode (visual or auditory), or combination of modes, to use for the presentation of route guidance information. The different display methods investigated were visual systems (current dashboard mounted display types) and auditory systems (computer generated voice communication systems). The second issue was the effect of different information processing codes on driver performance and workload. The information processing code determines the method used to present information to the driver using the display; in this research both verbal and spatial codes were considered. Verbally coded information consists of a series of sequential directions (for example, "go to the next street and turn right"), while spatially coded information is presented using a map display for visual systems.

Experimental Approach and Objectives

The approach used in this research concentrated on the relationship between task performance using navigational aids and cognitive theories. Multiple Resource Theory, Stimulus-Central Processing-Response Compatibility

Theory, Recoding Mechanism Theory, and Dual Coding Theory have been used to explain people's behavior when completing various information processing tasks. An experiment was conducted to look specifically at the change in performance with different types of navigational aids. Spatial ability has been linked to map reading performance. Since many navigational aids are employing the use of maps in vehicles, spatial ability was examined to determine if it has a significant effect on the task performance and subjective preferences.

The following experimental hypotheses state the research objectives in a testable way. Table 1 shows the predictions of the first four hypotheses. The dependent measures used for all hypotheses were number of wall hits, number of navigational errors, time to complete task, subjective workload questionnaire scores and subjective preference scores.

H_1: Multiple Resource Theory - Performance will be better when information is presented using a voice navigational aid.

H_2: Stimulus-Central Processing-Response Compatibility Theory - Performance will be better when information is presented using a map navigational aid.

H_3: Recoding Mechanism Theory - Performance will be better when information is presented using text or voice navigational aid.

H_4: Dual Coding Theory - Performance will be better when information is presented using a text or voice navigational aid and a map navigational aid at the same time.

Table 1. Predictions of first four hypotheses.

Navigational Aid	Multiple Resource Theory	Stimulus-Central Processing Response Compatibility Theory	Recoding Mechanism Theory	Dual Coding Theory
Map		best		
Text			best	
Voice	best		best	
Map and Text				best
Map and Voice				best
Text and Voice				

H_5: Spatial Ability -

- high SA subjects perform better with spatial navigational aids than low SA subjects
- high SA subjects will rate spatial navigational aids as less workload intensive than low SA subjects
- high SA subjects will prefer spatial navigational aids more than low SA subjects will

Dissertation Organization

This dissertation is organized into nine chapters. Chapter 1 introduces the topic area and the experimental approach and objectives of the research. Driving and navigation are discussed in Chapter 2 with special attention given to research completed on navigational aids in vehicles. Spatial ability is considered in Chapter 3 and cognitive theories are related to route presentation in Chapter 4. Chapter 5 explains the methodology that was followed during this study. The results are given in Chapter 6 and discussed in Chapter 7 with the conclusions drawn and future research stated in Chapter 8. The references are contained in Chapter 9 and the appendices follow.

II. DRIVING AND NAVIGATION

Overview

Emerging intelligent transportation systems technology will have a profound impact on the design of future driver interfaces. Human factors is an important component in the assessment of in-vehicle information systems (Jovanis and Kitamura, 1989). This chapter will address various aspects of driving and navigation. First, mental workload and the driving task will be discussed. Later, automobile displays, Intelligent Transportation Systems, and navigational aids will be explained.

Mental Workload

There is no widely accepted definition of workload. It is beneficial to try to predict human performance in a newly developed system by measuring the degree to which a driver is loaded to determine if alterations are required of the task (Wickens, 1992). Other definitions of workload include the following. "Mental effort is the integrated mental effort required to perform the primary task. It includes such factors as level of attention, depth of thinking, and level on concentration required by the primary task" (Casali, 1982). Eggemeier and O'Donnell (1982) state that many people think of mental workload as a multidimensional interaction of task and system demands, operator capabilities and effort, subjective performance criteria, and operator training and experience (Schlegel, 1993). The basic notion of workload is related to the difference between the amount of resource available within a person and the amount of resource demanded by the task situation (Sanders and McCormick, 1993). A simplified model of mental workload is shown in Figure 1 (Schlegel, 1993). The

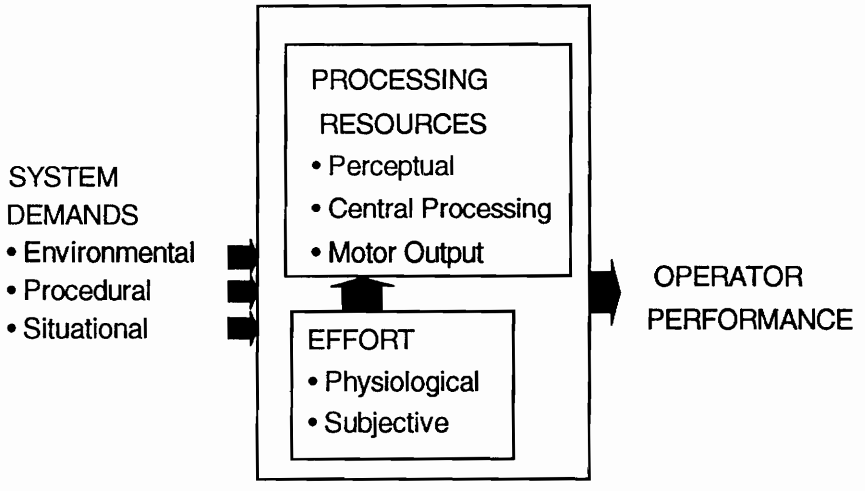


Figure 1. Simplified model of mental workload (Schlegel, 1993).

system demands are the external stimuli from the environment, task, and situation which require the operator to perform some response. These stimuli are perceived and processed by the operator only if attention resources are available. Once the stimuli are attended to, their processing consists of the operator's decision and response selection. This processing takes physiological and subjective effort on the part of the operator. Operator performance results when the response is executed and in some cases feedback is given. The definition of mental workload can be expanded to describe driver workload, which continuously changes with different phases of driving, such as vehicle control, navigation, and collision avoidance (Hancock and Parasuraman, 1992). Verwey (1993) adapts Wicken's (1984) workload definition to include drivers: "...the load on perceptual (visual, auditory, and tactile), central (cognitive), and output (hand, foot, and vocal) resources."

In-vehicle navigation aids require that attention previously given to another task or tasks be rerouted to the navigational information. The question of what amount of attentional change is safe needs to be answered. In other words, can the rate of accidents be predicted based on the level of workload experienced by a driver as a result of adding a navigational aid to the driving task? Antin, Dingus, Hulse, and Wierwille (1986) found a strong relationship between glance frequency to the in-vehicle display and the percentage of trials where lane crossings occurred, but did not find a relationship between glance duration and the percentage of trials where lane crossings occurred. This indicates that drivers may glance quickly and frequently at an in-vehicle display to see if changes have occurred, such as a turn coming up. If this is the case, then Dingus' (1987) suggestion to use an auditory warning device to alert the driver of an upcoming turn at an intersection may be an improvement to in-vehicle navigational displays. In-vehicle displays have a number of human factors design issues associated with them, in particular, the appropriateness of sensory modality chosen to transmit information to the driver. Automobile displays are discussed in detail in a future section.

Workload measures consist of physiologic, objective (primary and secondary task performance), and subjective methods. Physiologic methods are used to measure the effort required to perform a job. Since information processing involves central nervous system activity, this general activity or its manifestations can be measured. Examples of this method are heart rate, heart rate variability (sinus arrhythmia), blood pressure, peripheral blood flow, electrical changes in skin, respiration rate, ventilation, oxygen consumption, carbon dioxide estimation, brain activity, muscle tension, pupil size, finger tremor, voice changes, blink rate, and catecholamines.

Objective methods are performance oriented; they do not rely on the operator's opinion or physiology. Measures can be taken of primary task performance (in which no comparison is made of the task performance with the performance of any other task) and of tasks in a comparative situation. If a single task is being performed, it is possible to assume that variation in performance of that task reflects changes in workload; this is primary task performance. Comparative task performance is when two or more conditions are presented to a single subject group. Special cases of comparative task performance are information processing, secondary task and synthetic work situations. The logic behind using secondary task measures is that spare capacity, not being directed to performance on the primary task, will be used by the secondary task (Sanders and McCormick, 1993). As a result, the greater the demand for resources for the primary task, the fewer resources available for the secondary task and the poorer the performance on the secondary task.

Subjective assessments attempt to psychophysically measure whether or not the operator feels loaded or stressed. Some examples of subjective assessment techniques are Likert-type rating scales, the modified Cooper-Harper scale, the Subjective Workload Assessment Technique (SWAT), and the NASA-TLX. Hicks and Wierwille (1979) found rating scale measures (and primary task performance) to demonstrate greater sensitivity in measuring mental workload than secondary task performance, visual occlusion, and cardiac arrhythmia.

Useful measures of mental workload should meet the following criteria (Sanders and McCormick, 1993):

1. Sensitivity: The measure should distinguish task situations that intuitively appear to require different levels of mental workload.
2. Selectivity: The measure should not be affected by things generally considered not to be part of mental workload, such as physical load or emotional stress.
3. Interference: The measure should not interfere with, contaminate, or disrupt performance of the primary task whose workload is being assessed.
4. Reliability: The measure should be reliable; that is, the results should be repeatable over time (test-retest reliability).
5. Acceptability: The measuring technique should be acceptable to the person being measured.

Verwey (1990) reviews studies of driver workload and states that more than one method should be used to evaluate mental workload; Sanders and McCormick (1993) agree with the use of more than one measure for the assessment of mental workload. This study will use secondary task performance and subjective assessments to evaluate mental workload. The secondary task will be the use of the navigational aid and performance will be measured on the primary task of maneuvering. Subjective assessment will consist of a questionnaire given after the participant completes each scenario; the technique to be used is the Modified Cooper-Harper scale. This technique was chosen because Wierwille, Casali, Connor, and Rahimi (1985) recommend the Modified Cooper-Harper scale for perceptual tasks where the information is primarily visual. The task of driving is a perceptual task that is visual in nature. Driver workload will be considered in conjunction with the driving task in the following section.

Driving Task Description

"Driving is, in part, an information-processing task in which the driver receives input (from the vehicle as well as from the environment) concerning vehicle status, and on the basis of this makes certain control manoeuvres to operate the vehicle safely and efficiently" (Dewar, 1988). If workload is not considered, safety and efficiency may be compromised. Schlegel (1993) states that it is important to develop a macroview of the overall driving system so that the numerous interactions of vehicle, driver, road, and environment can be understood. Figure 2 shows the interaction of the subsystems: driver, vehicle, and environment (from Kramer and Rohr, 1982). Driving task elements, driver elements, and environmental elements are discussed in the following sections.

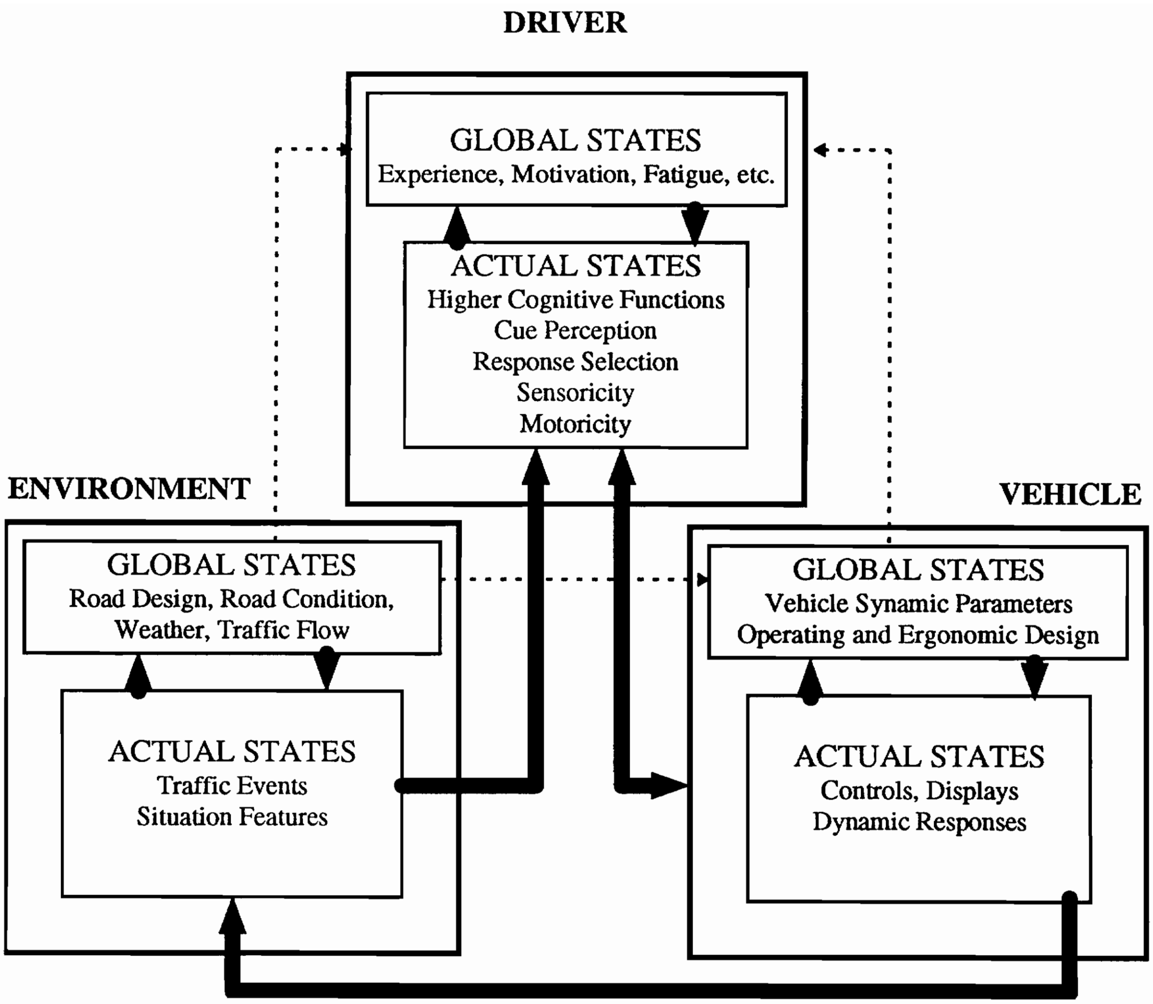


Figure 2. Interaction of the subsystems driver, vehicle and environment (from Kramer and Rohr, 1982).

Driving Task Elements. According to Schlegel (1993), the following driving task elements need to be investigated: vehicular guidance, navigation, communications and the social environment, operation and monitoring of systems, command decisions, and workload factors.

A driver is required to guide the vehicle by keeping to a lane, adapting speed, and reacting to obstacles, traffic signs, and other road users (Kramer and Rohr, 1982). The first two tasks are essentially tracking functions requiring visual-motor coordination. The third task requires visual scanning and auditory monitoring, decision making, and response selection and execution.

Vehicle navigation is a higher order process involving spatial abilities. Navigation or "way-finding" is the process of figuring out how to get from one place to another while remaining oriented (Petchenik, 1989). Drivers may get navigational information from an internal map or extract the information from a printed map, information signs, written instructions or an electronic navigation display system.

Communication within the automobile (e.g., conversations with passengers, listening to the radio, and using mobile phones) diverts a portion of attentional resources away from the driving task. Visual "communication" from road signs and vehicles displays takes further attention away from the driving task.

Since the driver is required to operate and monitor a number of systems in the automobile while driving, it is crucial that the design of the controls and displays do not strain the information processing abilities of the driver.

Command decisions in driving may be described as tactical planning and execution versus strategic planning. The relationship of command decision to driver workload is difficult to quantify but may be most critical in terms of leading to catastrophic human error.

Federal Aviation Regulation 25 outlines the following workload factors for aircraft (Schlegel, 1993):

1. The accessibility, ease, and simplicity of operation of all necessary flight, power, and equipment controls...
2. The accessibility and conspicuity of all necessary instruments and failure warning devices...The extent to which such instruments or devices direct the proper corrective action is also considered.
3. The number, urgency, and complexity of operating procedures with particular consideration given to the specific fuel management schedule...(Kantowitz and Casper, 1988).

These factors transfer to the automobile driving task with minimal modification. The major issue in driving as well as as navigation is how the workload components related to the design of the three major areas within the vehicle subsystem discussed above can be assessed in conjunction with the other major subsystems of the driver and environment (Schlegel, 1993).

Driver Elements. The general U.S. driving population "spans a wide range of ages and abilities, is culturally diverse, possesses a high degree of variation in behavior and attitude, and is not subject to regular proficiency or medical checks" (Schlegel, 1993). The amount of driver experience affects the level of automaticity of the driving task. As the level of experience increases the driver samples a greater portion of the environment, looking further up the road rather than strictly toward the right-hand side of the road.

Although drivers use all their senses when driving, vehicular guidance primarily involves visual-motor coordination. Therefore, the visual input of the information processing system, the driver, must be taken into account (Kramer and Rohr, 1982).

Age affects the driver's ability to process information and react quickly. Typically, elderly individuals are slower at eye movements and because of poor visual acuity, they take longer to obtain pertinent information (Dewar, 1988). Since older drivers are more sensitive to glare and their lenses are slower to accommodate, it takes them longer to obtain visual information.

Drivers under the influence of alcohol and other chemical substances have reduced capacity to react quickly and assimilate information properly.

Schlegel (1993) states that aside from the previously mentioned factors, there are a number of individual differences or personality variables that may affect workload assessment and the actual level of workload itself. Adaptation level, personality factors, motivation, and time of day are a few. Differences in perceptual style (field independent vs. field dependent) and selective attention ability are related to automobile accident involvement.

There are two driver characteristics that are related to navigation specifically: spatial ability and cognitive mapping. These are discussed in detail in the next chapter.

Environmental Elements. In driving tasks there are two distinct environments: internal and external. The major elements of the internal environment are temperature, sound and noise, lighting, vibration, acceleration, and the social environment (Schlegel, 1993). The interaction of these greatly affects driver workload and driving performance. The external environment includes roadway design, traffic signals and speed limits, road surface, time of day or night, lighting, weather conditions, traffic conditions, and the movement patterns of other drivers.

Automobile displays are used extensively in the driving task for the presentation of both vehicle status and task information. They are discussed in detail in the following section.

Automobile Displays

Visual displays have been used to present information on the status of various vehicle systems to drivers since the advent of the automobile (Fowkes, 1984). The presentation of information to the driver must be reviewed with the advent of new display technology. In this context the visual display is the interface between the driver and vehicle. Advances in electronics have led to profound changes in vehicle display technology. In addition to traditional information, such as fuel level, there are now warnings for open doors and unengaged seat belts, gauges for outside temperature, monitoring for estimated time of arrival, and aids for navigation. Fairclough and Maternaghan (1993) and Noy (1989) state that intelligent displays in vehicles can intrude on driving. "The growing intelligence of driver interfaces may offer important opportunities to enhance safety, improve driver comfort and convenience and reduce travel time and fuel consumption. However, the extent to which new technology can deliver such benefits depends largely on the ergonomics of the driver interface" (Noy, 1990). There are two important aspects of display design to consider, visibility and legibility. A display that is visible may be seen correctly by the driver, while a display that is legible is also correctly understood by the driver (Fowkes, 1984). Fowkes (1984) lists four groups of factors that impact display design: human, environmental, display, and task factors. These are shown diagrammatically in Figure 3 and each are discussed in Tables 2 to 5, respectively.

Automobile displays are an integral part of all aspects of Intelligent Transportation Systems. These systems are discussed in the following section.

Intelligent Transportation Systems

Intelligent Transportation Systems (ITS) will change the driving task and the way traffic is managed in the U.S. (Mast, 1991). ITS were previously known as Intelligent Vehicle Highway Systems or IVHS. These systems refer to an integrated group of technologies which will save lives, save time, and save money (IVHS America, 1992). ITS can improve safety, reduce congestion, enhance mobility, minimize environmental impact, save energy, and promote economic productivity in our transportation system (IVHS America, 1992; Lund, 1991; Perez and Mast, 1992; Rillings, and Betsold, 1991). Lee, Morgan, Raby, and Wheeler (1994) state that a driver-centered design philosophy will promote these benefits. These advanced technologies will thereby enhance the safety and efficiency of automobile transportation (Hancock and Parasuraman, 1992) but developing systems that can be safely and effectively used by drivers who have a wide range of physical and mental abilities is one of the most difficult

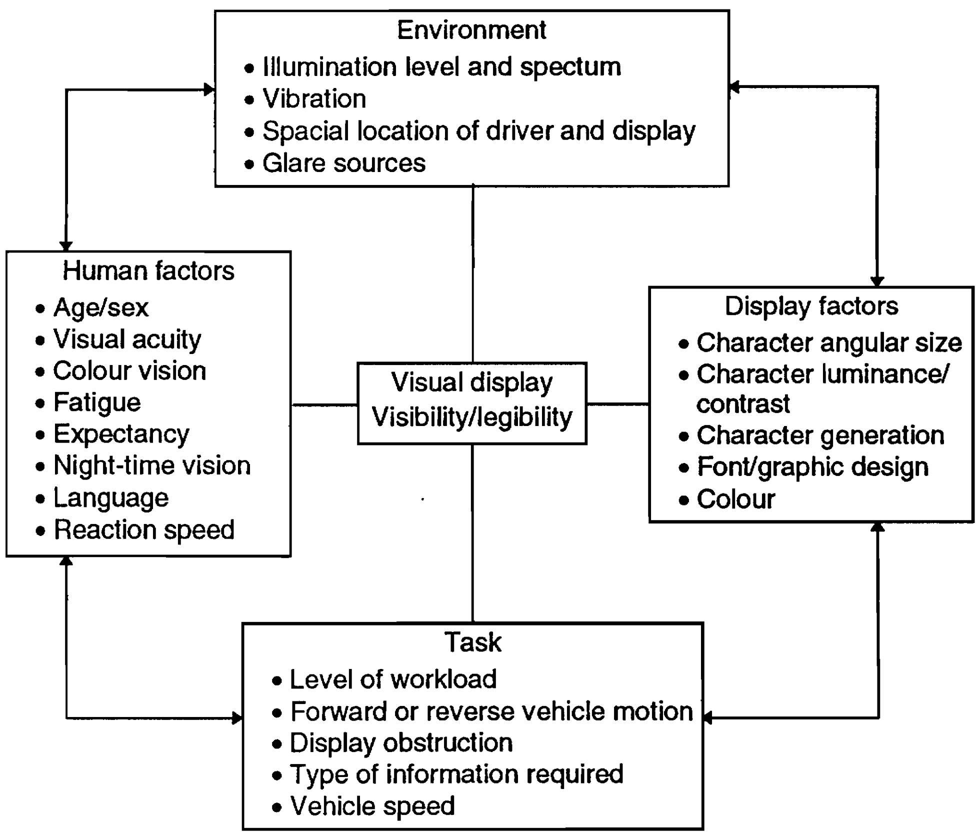


Figure 3. Driver-display interface factors (Fowkes, 1984).

Table 2. Human factors (Fowkes, 1984).

Human Factor	Description
Age	The driving population ranges in age from 17 to more than 90 years old. Many aspects of human ability suffer impairment with increased age. Visual performance also follows this trend. Visual acuity and colour sensitivity are two examples, and their age effects are discussed below. Accommodation, or the ability of the eyes to focus at different distances, is affected by ageing. The nearest focusing distance for the normal 16-year old can be 80mm. This may increase to 250mm at 45 and to 1 metre at 60. RESULT: In specifying character size for displays used by the full range of drivers in the population, particular note must be taken of those over 60 years both in terms of acuity and accommodation.
Sex	The main characteristic of importance which is related to sex is colour vision occur mainly in the male population. RESULT: See colour vision below.
Visual acuity	Visual acuity can be described as the ability of the eye to resolve fine detail. The effect on performance depends on the size of target and its brightness. Consequently the level of illumination present and the contrast between target and background are important contributory factors in determining visual performance. This ability is age-dependent, ie with increased age visual acuity decreases. Some sources suggest performance decrements of 50 per cent for the population of 40+ compared to the 20-40 age group. Therefore drivers over 40 may require up to twice the character size as those younger at threshold values. Visual acuity is also impaired under night time conditions. RESULT: Again the age effects of acuity require a close consideration of the needs of the older driver.
Colour vision	Deficiencies in the colour discrimination ability of the population occur particularly in the male population. There are many forms of colour vision deficiency but the most common are difficulties in discriminating between read and green or blue and yellow. In addition colour discrimination generally deteriorates with increased age. RESULT: Once more the requirements of a portion of the population dictate the requirements for the overall population. Colour combinations to avoid are red/green and blue/yellow due to confusion problems.
Fatigue	Fatigue in the context of driving is an important factor to consider where the question of crucial event information is concerned. Fatigue effect upon the driver are shown, in increasing order of importance; in inattention to individual components of the driving task, erratic visual search behaviour, and finally short periods of unconsciousness or 'microsleep'. A display cannot eradicate these effects, of course, but crucial event information should attract attention in an attempt to counter the less severe fatigue effects. RESULT: All crucial event information should be 'attention' attracting to the driver.

Table 2. Human factors (Fowkes, 1984) (cont.).

Human Factor	Description
Expectancy	The driver population as a whole has expectancies of the information and format of information given by vehicle displays. In terms of general format the common fixed scale-moving pointer display has been present in practically all vehicles for major display functions. Hence the driving population expect this format, and are trained to use it. Colour coding such as 'red' warning lights, 'blue' main headlamp beam etc. are accepted and standardized. However symbology for functions differs between populations. RESULT: Novel display formats should be evaluated for their potential acceptability by target populations before use. Careful note of population expectations should be undertaken before design for any particular market.
Night-time vision	The eye uses two mechanisms of the retina to detect light. These are described by their functional units in the retina, the rods and cones. The cones are primarily sensitive to the wavelength of light and therefore colour, and are predominant around the optical axis of the eye. The rods are more sensitive to the amount of light present and are mainly situated at the periphery of vision. RESULT: Colour discrimination at the periphery of vision during night-time conditions is seriously impaired. Therefore crucial event information is required to be sufficiently attention seeking to attract the central gaze of the eye which is more sensitive to colour.
Language	This applies mainly to alphanumeric displays which could present information in a written form. Intelligibility should be assessed for all countries where the vehicle will be used. RESULT: Consider target markets in providing coded information.
Reaction speed	There is variation amongst the driving population in almost every respect, including response speed. In terms of visual display this requires consideration of the format and content of information so that it is easily assimilated by the slowest responders. RESULT: Evaluation of novel designs requires testing by a wide range of subjects from the population.

Table 3. Environmental factors (Fowkes, 1984).

Environmental Factor	Description
Illumination level and spectrum	The illumination level found at the instrument and spectrum panel surface of a passenger vehicle is of course variable with the time of day and season of the year. For European driving it may be estimated that the range of levels may be from 0.01 lx (moonlight) to 60,000 lx (direct side window solar illumination). The spectral qualities of the illumination present in a vehicles can be variable. Daylight conditions, where the sun is the light source, provide wide-band illumination even though this can take on pronounced casts depending upon solar altitude. However, more veiling illumination is provided by narrow-band emitting artificial road lights. RESULT: High levels of direct illumination can cause wash-out of active displays, and colour of the incident light can greatly influence visibility, particularly of narrow-band emitting warning lights. Evaluation techniques for displays must accurately recreate both level and spectra of representation vehicle ambient illumination ranges, taking careful note of any specific operating conditions of special purpose vehicles.
Vibration	Vibration induced in both the driver and any visual display in the instrument panel is created by complex interaction of the road surface, tire and suspension characteristics. The result is a variable acceleration/frequency pattern during driving. Typical values noted for passenger cars are 0.16 ms^{-2} at 4 Hz and 0.1-0.3 ms^{-2} at 11 Hz. If a vehicle is due to operate under environments where more extreme vibration conditions may occur then of course more substantial effects may be seen. RESULT: If vibration levels are likely to be severe then careful consideration of this factor is required perhaps to increase subtended angle of characters.
Spatial location of driver and display	The fascia/seating package of a vehicle imposes driver and display basic limitations on the display factor of subtended angle. For most normal passenger car packages a typical display viewing distance is 800 mm, and this has been used in this study. The angle of view of the display is also controlled by the manner in which the display is mounted in the fascia relative to the direct line of sight to the driver. RESULT: Current packaging suggests 800 mm as an acceptable viewing distance for the character sizes use in current visual displays, ideally placed so that the deviation required from the normal line of sight is minimized and that the displays are viewed normally.
Glare sources	These may be either natural sources (ie sun, either viewed directly or reflected) or artificial sources (vehicle headlights or roadside lights). Evidence from experiments suggests that current practice glare levels and display characteristics are not sufficiently near threshold values for this factor to be a problem. RESULT: If the level of glare is exceptional due to predicted operational conditions then further consideration should be given to display visibility factors.

Table 4. Task-related factors (Fowkes, 1984).

Task-related Factor	Description
Level of workload	The level of workload current on a driver during a journey is very variable. Quiet, relatively 'straight' rural roads offer relatively little workload in comparison to a congested town centre. In the context of visual displays this may seem that at times during a journey a driver has little or no spare capacity to view his instrument panel mounted display. RESULT: The 'worst case' road situation which provides a high workload for the driver can completely interrupt the subsidiary task of periodically viewing the displays. If crucial event information (such as oil pressure failure) is to be conveyed to the driver successfully under these situations then it has to be of a form that can attract his attention, possibly by using a non-visual mode
Forward or reverse	This is the most obvious task-related factor to provide an interruption to the diver's ability to inspect his visual displays. When reversing a vehicle, the driver's view is normally directed rearwards and therefore away from the instrument panel. RESULT: As with 'level of workload' display reading tasks are potentially interrupted. Similar comments therefore apply. If crucial event information is to be given it must attract the driver's attention.
Type of information	A crucial factor is the appropriate determination required of type and format of information display. Various classification have been advanced to describe the type of information required by a user from a display. Briefly, these can be described as quantitative, qualitative, check, and status/warning information. These are the principal visual display uses in a vehicle. Although with the future of electronic displays in mind, a fifth category which is the more detailed descriptive information provided by alphanumeric/symbolic displays may also be included. RESULT: In any assessment of a complete instrument panel design careful consideration should be given to each individual displayed item of information. What form of information is required from the display and how is this information coded to the driver in relation to all other displayed functions?
Vehicle speed	A special example of increased workload with higher vehicle speeds. Under motorway conditions, for example, the driver's visual search of the road is increasingly further ahead of the vehicle. Any distraction form this to inspect the instrument panel requires not only a substantial re-accommodation of the eye, but also causes a greater penalty in terms of road distance covered without the driver's view being directed to the road. RESULT: At high vehicle speeds the need for speed of reading from visual display is very much greater.

Table 5. Display factors (Fowkes, 1984).

Display Factor	Description
Character angular size	The minimum acceptable size of a display character (normally expressed in minutes of arc) size is most closely related to the visual acuity of the driver and the location of the display. Taking note of character contrast, ambient illumination level, character font, human factors etc. these have been accounted for. The minimum value suggested for accurate reading is: RESULT: 20 min. of arc (ie 4 mm viewed at 800 mm)
Character luminance/contrast	In general terms, the legibility of any display is increased with greater contrast between symbol and background. In vehicle use this factor influences legibility as much as any other. Given many sources of research, and taking the minimum character angular size noted above, it is suggested that the value below should give acceptance legibility to the driving population. RESULT: At least 8:1; however, colour contrast is still in need of further research.
Character generation	For alphanumeric information in particular, two forms of character generation are available, segmented or dot matrix designs. Various studies have been performed in a variety of technologies attempting to assess the relative legibility of these formats. RESULT: The more segments present in a segmented display, ie seven segments and above then the greater the flexibility of character which may be presented. However, in most comparisons if contrast ratios are kept to acceptable levels (as given above) little difference is found between seven segment and various dot matrix characters (see below).
Font/graphic design	The graphic design or font of alphanumeric characters has been investigated at length by many researchers, much of the work referring to printed characters on conventional displays. This has evaluated many aspects of stroke-width and width-height ratios. RESULT: Many studies have shown remarkable small differences between fonts evaluated in dot matrix form: ASCII, Lincoln/MITRE and NAMEL are amongst those shown to be very similar in legibility tests. However, it is suggested that to display a range of non 'alphanumeric' symbols greater flexibility of character generation is needed than that available on a seven-segment character.
Colour	Colour vision deficiencies within the male population require that the use of colour within display designs in general should be controlled. There are, of course, existing legal requirements for colours used for displaying certain functions. Separating status and warning lights may be an important consideration, to provide position as well as colour coding of types of information along with any associated symbol, for particular vehicle functions. RESULT: It is important to consider display colour problems with particular reference to colour discrimination, combination of colours and symbology.

Table 5. Display factors (Fowkes, 1984) (cont.).

Display Factor	Description
Others	Current advances in electronics enable us to consider which sensory modalities should be used in specifying displays. Previous comments have suggested that crucial event displays (such as 'low oil pressure', 'overheating' and 'no fuel' warning require immediate action on the part of the driver. For a visual display to have the required attention attracting characteristics then briefly flashing 'emergency' lights or auditory signals could be used as a back-up to 'request' attention to the status/warning displays. RESULT: Modern electronics will enable a range of auditory messages to be presented to the driver whether in symbolic (ie buzzer/bell etc.) or verbal form to require attention to a particular vehicle function. The integration of audio and visual presentation of information could prove a significant improvement to the notification of vehicle system state by simplifying the visual load of the driver.

design problems yet to face system developers (Wheeler, Lee, Raby, Kinghorn, Bittner, and McCallum, 1994).

Advanced Traveler Information Systems (ATIS) are technologies which assist travelers with planning, perception, analysis, and decision-making (Transportation Research Board, 1993). Previously, they were known as Advanced Driver Information Systems (ADIS). The development of good ergonomic design guidelines for ATIS systems is especially important because of all the ITS systems, ATIS will probably require the greatest amount of interaction between the driver and the system (Wheeler et al., 1994). Human factors research for ATIS can be divided into two categories, ergonomic/anthropometric issues and cognitive/utilization/acceptability issues (Rillings and Betsold, 1991). The following section discusses the applied research carried out on the ergonomic/anthropometric issues, while chapters 3 and 4 address some of the cognitive issues.

The major goal of ATIS is to improve the information that is provided to drivers (Perez and Mast, 1992). To accomplish this goal, there are several subsystems within ATIS: 1) In-vehicle Routing and Navigational Systems (IRANS), 2) In-vehicle Motorist Services Information Systems (IMSIS), 3) In-vehicle Signing Information Systems (ISIS), and 4) In-vehicle Safety Advisory and Warning Systems (IVSAWS).

This research will be dealing with IRANS. IRANS provide drivers with information about how to get from one place to another, in addition to information on traffic conditions, and recurrent and non-recurrent urban traffic congestion (Mast, 1991; Perez and Mast, 1992). The systems may be passive (transmitting information only) or active (capable of calculating, selecting, and displaying optimum routes based on reception of real-time information from traffic control centers). Existing systems are discussed in papers by Burgett (1991); Catling, Harris, and McQueen (1991); Catling and McQueen (1990); Chen, Ho, and Lee (1991) ; Chen and Galler (1990); Fleischman (1991); Fleischman, Carpenter, Dingus, Szczublewski, Krage, and Means (1991); Jeffery, Russam, and Robertson (1989); Johns (1991); Katakura and Saito (1991); Kishi, Asami, Ishikawa, and Itoh (1990); McCauley, Clarke, Sharkey, and Dingus (1994); McQueen and Catling (1991); and Siuru (1990). Green, Serafin, Williams, and Paelke (1991) describe the functions and features to be included in driver information systems of the future, while Shields (1991) presents a projection to the end of the century of how in-vehicle navigation systems will evolve. The following section describes navigation aids in detail.

Navigational Aids

Spatial navigation is "one of the most basic abilities and essential survival skills of humans and most other animals" (Mark and McGranaghan, 1986). Drivers require information in order to reach their destination when traveling in a partly or totally unfamiliar environment (Verwey, Alm, Groeger, Janssen, Kuiken, Schraagen, Schumann, van Winsum, and Wontorra, 1993). Since one of the most mentally demanding tasks for an automobile driver is to maneuver in an unfamiliar environment (Streeter and Vitello, 1986), navigational aids are being developed to assist in this task. There are two types of information needed for error free navigation: pre-information to formulate a trip plan and in-transit information to follow the plan" (Lunenfeld, 1989). Dingus, Hulse, Krage, Szczublewski, and Berry (1991) studied pre-drive information. This research deals with in-transit navigational aids only.

With advances in microprocessors and artificial intelligence, automobile navigation systems are undergoing rapid technological evolution (Noy, 1989). Although drivers have used paper maps successfully for a long time, these maps have limitations which may be overcome with the use of vehicular navigation aids. The purpose of vehicle navigation (or map display) systems is to show the current vehicle location on a map and assist the driver in finding the desired destination (Suchowerskyj, 1990). Maps may appear "north-up" in which vehicle heading does not affect the orientation of the map or "heading-up" where the top of the map corresponds to the direction the vehicle is facing. Even though drivers have information about their current location, destination, and connecting road networks, they still must decide which way to go. Route guidance systems provide instructions by graphic symbols and/or by synthesized speech. Upon entry of a destination the recommended route is highlighted on the map display.

In-vehicle navigational aids should provide relevant, timely, and useful navigation information so a driver may respond in a safe and efficient manner. Poor interface design and workload regulation are two important issues that human factors specialists have reacted to in aviation; these issues can be treated proactively in the design of ITS (Hancock and Parasuraman, 1992). A major human factors concern is that the addition of visually displayed information may divert visual attention from primary visual tasks (Dingus, Antin, Hulse, and Wierwille, 1988; Fleischman, Carpenter, Dingus, Szczublewski, Krage, and Means, 1991; McGranaghan, Mark, and Gould, 1987; Rockwell, 1972). The information should be provided in such a way as to maximize the ability of the driver to extract the information from the displays without degradation in driving performance (Fleischman et al., 1991).

According to Antin (1993) some of the fundamental issues related to automobile navigation are:

1. What and how much navigation-oriented information is needed by the driver?
2. How and when should it be presented?
3. What are society's needs regarding navigation and traffic management?
4. What is the most cost-effective way to meet those needs?

Kishi and Sugiura (1993) discuss the human factors to be considered during the various development phases of route navigation and guidance system (Table 6).

The basic type of information needed for navigation is procedural knowledge in the form of a list of instructions; for example, turn right onto Prospect Avenue, go two blocks to Union Road and turn left. This is especially important in unfamiliar areas because this basic level of the cognitive map has not been developed. Maps (paper maps and moving-map displays) and other navigation aids (both spatial and verbal route guidance) may be used to help the driver arrive at the desired destination. All vehicle navigation aids need to have a minimum of two basic pieces of information: distance and direction from the current location to the desired destination. Compass information may also be included. The following paragraphs describe the various types of navigational guidance systems with the simplest types explained first.

Paper maps show the complete network of roadways with optional additional information such as landmarks. One advantage to this type of navigational aid is that the whole map is available at all times. If a navigation error is made, the driver can plan a new route from the current location. There

Table 6. Development phases of route navigation/guidance systems (adapted from Kishi and Sugiura, 1993).

Phase	Human factors
1. Select the information which should be provided	Necessary information for driving actions when driving unfamiliar roads (either voice or display is acceptable) a) What to provide ⇒ kinds of information b) At what timing ⇒ proper timing to provide information
2. Assignment of functions to voice and display interfaces	Features of the auditory device and the visual device for route guidance
3. Setting up the expressions of voice guidance	Expressions for ease of understanding on various routes and forms of turning points

are several disadvantages to using paper maps. Because the paper map contains the entire roadway network on a static structure, there may be a problem with scaling and clutter. The map must be large to include the information and may be dangerous to use while driving. The challenge to the spatial ability of the driver is the requirement to determine the vehicle location and orientation mentally, and select a suitable route.

Moving-map displays are the next level of navigational aid. These displays show the specific location and orientation of the vehicle on the map and can be operated as heading-up or north-up. An advantage of operating in heading-up mode is that the ego reference frame (ERF) always coincides with the world reference frame (WRF), which requires no mental rotation. Conversely, the advantage of the north-up display is the consistency between the user's sense of compass directions (WRF) and the display of these directions (Antin, 1993). These reference frames are described in Chapter 3. In the context of aviation, a moving-map display in a heading-up orientation makes the navigation task much easier by performing the location and orientation tasks for the operator (Aretz, 1988; Aretz, 1989).

Using moving-map displays does not guarantee that explicit route guidance is provided. A route selection algorithm generates a complete set of instructions to be presented to the driver (Antin, 1993). The algorithm can be programmed to select the shortest path, the simplest route, or the shortest time to destination. The route can be shown to the driver by changes in the color or intensity of the map, by directional arrows, or verbally (either aural or written). Ram and Al-Awadhi (1989) address the development of a navigational aid for road travel, including storing information about the road network, generating the shortest route between points, and converting the route into a set of easily understood instructions. The design of the Chrysler passenger car navigational unit is described by Cyganiak (1987). He states that the most important factor, from the standpoint of safety, is the operator's attention to the operation of the vehicle.

The assignment of functions to voice and display interfaces (Phase 2 from Table 5) requires the consideration of the type of information to be presented. According to Ross, Vaughan, and Nicolle (1994) no guidelines exist for the best mode, or combination, of modes (visual or auditory) to use for the presentation of route guidance information. Barb and Mast (1992) also state that there is a need for research in the area of sensory display modes and the associated information format that is most appropriate for individual ITS functions (Dingus and Hulse, 1993). Table 7 shows a comparison of audition and vision in information presentation for generic applications.

The following subsections give examples of various research with incompatible findings on the best way to present navigational information to drivers. Akamatsu, Yoshioka, Imacho, and Kawashima (1994) felt that, in order to design a user interface of a car navigation system, it was important to know how the driver would use the system while driving, primarily what was important information for the driver. They found that landmarks such as buildings and street names were important for the identification of crossroads. Bonsall and Parry (1990) found that drivers would not like route guidance information for familiar areas. Their interviews also suggested that most people opted for a time minimizing system while a substantial minority wanted one that had the ability to trade-off between time and distance.

Table 7. When to use the auditory or visual form of presentation (Sanders and McCormick, 1993).

Use auditory presentation if:	Use visual presentation if:
1. The message is simple.	1. The message is complex.
2. The message is short.	2. The message is long.
3. The message will not be referred to later.	3. The message will be referred to later.
4. The message deals with events in time.	4. The message deals with locations in space.
5. The message calls for immediate action.	5. The message does not call for immediate action.
6. The visual system of the person is overburdened.	6. The auditory system of the person is overburdened.
7. The receiving location is too bright or dark-adaptation integrity is necessary.	7. The receiving location is too noisy.
8. The person's job requires moving about continually.	8. The person's job allows him or her to remain in one position.

Verbal Code. Parkes, Ashby, and Fairclough (1991) report two studies that suggest that simple verbal instructions present the driver with the least amount of distraction, which should be augmented with visual confirmation since verbal instructions are transient. Streeter, Vitello, and Wonsiewicz (1985) also found that properly designed vocal instructions to be a better navigational aid.

Fairclough and Maternaghan (1993) investigated the consequences of driver visual overload by comparing the effects of a paper-based map display and a computer-based text display of route navigation information on driver behavior. They found that drivers were forced to spend more time viewing the map display during the experimental trials.

Two studies by Labiale (1990) investigate the effects of presentation modalities (visual/auditory/repeated auditory) and complexity levels of in-car road information. The results showed that short auditory messages or auditory messages used as a prompt to a very simple visual map optimize driving performance. Written presentation of road information would be most useful when the car is at rest.

Schmandt and Davis (1989) are developing the “Back Seat Driver,” a prototype of a system to use speech synthesis as a navigational aid in automobiles. Their results suggest that speech may prove to be a “powerful technology in automobiles of the future.”

Spatial Code. Shekhar, Coyle, Shargal, Kozak, and Hancock (1991) present two experiments that examine headup displays as one method of presenting navigational information. Since a vital facet of information presentation is synthesis and management, displays should not overload drivers and create safety hazards in and of themselves. The first experiment evaluated the differences in driver response to alpha-numeric versus iconic headup displays. The second experiment compared ego-centered against fixed-based map representations of geographical information. Results indicate the superiority of iconic headup displays and ego-centered maps.

Mollenhauer, Lee, Cho, Hulse, and Dingus (1994) studied subjects in an interactive driving simulator that were presented with road sign information from a visual dash mounted LCD display or from digitized auditory voice. They found that presenting information in an auditory mode results in a higher level of road sign information recall, but also decreases the subject's driving performance when compared to a visual display. Subjects rated auditory information as more distracting than visual information.

Popp and Farber (1991) compared displays with route guidance advice in the form of alphanumeric text strings, symbolic advice, and maps with different levels of complexity. They found that the symbolic representation of route guidance information is superior to the other presentation modes and that even optimally designed maps have no positive effects on driver's orientation, reduction of workload, or traffic safety behavior. Also, they found all route guidance displays to force drivers to observe them intensively, therefore shifting their attention away from traffic.

Antin, Dingus, Hulse, and Wierwille (1990) evaluated navigation performance associated with the use of a moving-map display, a conventional paper map, and a memorized route which served as a baseline for comparison. They found that the quality of routes selected with the paper map or moving-map did not differ. However, the moving-map drew the driver's gaze away from the driving task significantly more than for either the paper map or memorized route.

In the same study Antin, Dingus, Hulse, and Wierwille (1988) studied the effect of spatial ability on performance with the two map methods of navigation; it was not significant. Dingus, Antin, Hulse, and Wierwille (1988) evaluated the relative effectiveness and efficiency of three methods of navigation: memorized route, conventional paper map, and the navigation system. They found that subjects spent more time glancing at the navigator than the paper map, and the navigator drew the subjects' glance away from the driving task significantly more than the memorized route or the paper map.

Wierwille, Hulse, Fischer, and Dingus (1988, 1991) describe two experiments determining the visual adaptation of the driver to high-demand driving situations while using an in-car navigation aid. They found that for increases in both anticipated and unanticipated driving demand, drivers increased the proportion of time spent on the forward central view (out the windshield of the car) and decreased the proportion of time spent observing the in-car navigational aid.

Burnett and Joyner (1994) investigated the safety-related implications of route guidance systems. They used two conditions: one was a moving map-based route guidance system and the other was either a map with notes or verbal instructions. While they found subjective response to the moving map-based system very positive, the use of the system was associated with high visual distraction.

Aretz (1990) compares a visual momentum map display with traditional track-up (heading-up) and north-up approaches for pilot navigation tasks. The visual momentum map attempted to capture the benefits of the north-up map (developing a cognitive map of the area) while reducing the costs (lack of congruence with ERF).

Spatial and Verbal Codes. Kimura, Maranuaka, and Sugiura (1994) investigated human interface specifications for voice route guidance in an experiment with four subjects. They found the effectiveness of the voice plus display guidance system included a reduction of visual and mental workload over a display only system.

Srinivasan, Jovanis, Yang, and Kitamura (1994) conducted experiments to evaluate distraction, workload, and perceptions of four route guidance systems: paper map (control condition), heads down electronic map, heads up guidance display (HUD) with heads down electronic map, and voice guidance with heads down electronic map. They found that subjective workload, user perceptions, and navigation errors indicated the voice guidance/electronic map combination to be the best and the paper map to be the worst. The reaction time data also indicated the paper map to be the worst but did not clearly indicate which electronic device was the best.

Verwey et al., (1993) state the following recommendations for a navigation system. The systems should be able to present both oral and visual information; this will give the driver the opportunity to select the source of information depending upon the demands of the road and traffic situation and to confirm the last oral instruction. The content / meaning of the oral and visual messages should be the same. The visual messages should consist of arrows, pointing in the required direction of travel. The oral messages should consist of simple instructions such as “turn left” and “turn right.”

Labiale (1989) studied in-car navigation displays using different information presentation modes (map alone, map and auditory guidance, and map and written guidance) with different levels of complexity. He found out that the map presentation with written directions resulted in a majority of drivers being able to recall the route to follow. This may be due to the fact that the drivers are able to read the written information several times unlike the auditory situation. Maps with auditory guidance were preferred over maps alone and maps with written guidance. Labiale suggests a map with aural guidance information while driving would constitute the best display.

This review of the route guidance and navigational aids literature shows that, depending on what system is used, results indicating the optimal type of navigational aid vary. Rather than looking at only the navigational aid, attention must also be directed at the driver's needs and behaviors. Mark and McGranaghan (1986) and McGranaghan, Mark, and Gould (1987) stress that the relative importance of the "verbal vs. spatial" codes and "aural vs. visual" modalities must be explored. This research will address codes and modalities in conjunction with cognitive theories and abilities. The following chapter discusses spatial ability and its effect on using navigational aids. Chapter 4 explains four cognitive theories which may be used to predict performance in navigation systems. Ability to predict performance is important for the engineers designing navigational aiding systems.

III. SPATIAL ABILITY

Overview

Two driver attributes that are related to navigation are spatial ability and cognitive mapping. Spatial ability and cognitive mapping are important to understand since they vary widely over individuals; drivers will react to navigational aids in a way that is consistent with their own personal attributes. Rillings and Betsold (1991) state that the cognitive issues involved with navigational performance is not generally understood. They recommend that studies investigating cognitive spatial mapping be done. This chapter will describe the issues and propose a means to study them.

Spatial Ability

Spatial ability, which is the "ability to perceive spatial patterns and to compare them" (Corsini, 1987), characterizes "the facility with which one stores, organizes, recalls, and utilizes information pertaining to the relationships among objects in a given space" (Antin, 1993). Navigational tasks, especially those relating to the reading of a map, involve similar abilities and the level of spatial ability a driver has can affect the performance on tasks requiring the use of map-like navigational aids. Individual differences with regard to spatial ability will also be an important determinant of navigation behavior (Antin, Dingus, Hulse, and Wierwille, 1988). "The degree of mastery of the map-reading task is highly associated with normal variations in spatial ability" (Streeter and Vitello, 1986). In general, people with high spatial ability acquire an accurate representation of an environment from either a map or from navigation faster than low ability subjects (Stasz and Thorndyke, 1980; Thorndyke and Hayes-Roth, 1982). Since the navigational aid must be usable by drivers with low as well as high spatial ability, spatial ability will be used as an independent variable. If some of the aids are not easily used by those with low spatial ability, then they should not be considered as viable alternatives for the mass market.

Lohman (1979) identified three subcategories of spatial abilities: moving the mind's eye to a new perspective (spatial orientation), rotation and related transformations of mental images (spatial relations), and complex folding and distortion of the object (spatial visualization) (Carter and Woldstad, 1985). Some people feel that spatial orientation and spatial relations are the same factor since they both involve mental rotations, and similar tests are often used for both (Ekstrom, French, and Harman, 1976). "In general, the construct of spatial ability can be seen as the ability to store, organize, and recall information pertaining to shapes and fields and the relationships among items within those fields" (Antin, 1987).

Since there is some understanding of processes required for map learning (Thorndyke and Stasz, 1980), there is some basis for selecting particular abilities to measure. Stasz and Thorndyke (1980) identified two abilities that seem related to the task of map learning: field-independence and visual memory. Field-independence (FI) and field-dependence (FD) are cognitive styles that relate to preferred strategies of information processing. FI can be measured by perceptual tests in which the problem must be solved by surmounting some visual or postural context. Since maps hold a great deal of visual information, this ability is important. The second ability was visual memory, which is the ability to remember the configuration, location, and orientation of purely spatial or pictorial information. Since there is a large amount of spatial information on maps, this ability is also important.

Antin, Dingus, Hulse, and Wierwille (1988) reported a study which showed that people with higher spatial ability (determined from tests) spent a smaller proportion of driving time looking at available map information than those with lower spatial ability. Aretz (1989) characterizes navigational awareness as "the mental alignment of two frames of reference: 1)the ego centered reference frame (ERF) that is established by the forward view out of the cockpit, and 2) the world centered reference frame (WRF) that is established by the aircraft's location on a map." The two frames of reference have been used by Antin (1993) and Aretz (1989, 1990). Selective attention ability has also been shown to affect the accident histories of individuals (Avolio, Kroeck, and Panek, 1985). The importance of this is exaggerated in the use of navigational aids, especially visual aids.

Cognitive Mapping

A cognitive map is formed when an individual develops a mental representation of the relationships among objects in a given space. "It is an individual's inherent spatial ability as well as experiences with a given space (or its representation) which determine the content and extent of the cognitive map and how it may be used to solve real navigational problems associated with that space" (Antin, 1993). Cognitive maps can exist in different stages of development (Byrne, 1979; Kuipers, 1983; Thorndyke and Hayes-Roth, 1982). Thorndyke and Hayes-Roth (1982) have identified two categories of mapping knowledge: procedural descriptions and survey knowledge. Procedural descriptions are characterized by "the ability to navigate within an area based on a cognitive map encompassing landmark locations, and the basic directions and connections (nodes) among key roadways" (Antin et al., 1988). Fundamentally, they are based on the ERF. Survey knowledge, on the other hand, is "encoded in a more global form and includes such things as the absolute location, size, Euclidean distance, and directional relationships among key nodes and links within the area" (Antin et al., 1988). This is based on the WRF. The cognitive maps that are developed from navigational aids are influenced by the previously discussed levels of spatial representation.

Testing Spatial Ability

Antin et al. (1988) used three factor-referenced tests to measure individual differences in specific aspects of spatial ability relevant to automobile navigation. Perceptual speed was deemed important because success in navigation depends on the speed with which cues can be perceived from the environment, including the navigational aid. The Identical Pictures Test was used to measure this construct. Since navigation requires the ability to maintain bodily orientation with respect to objects in space, the spatial orientation factor was measured. The Cube Comparisons Test was used for the construct. Spatial scanning was considered relevant since the ability to visually explore a wide or complicated spatial environment under time stress is important in navigation. The Map Planning Test was used to measure this construct. They found that the scores on each test were significantly correlated with the other two. This shows that the tests measure similar constructs. "Even though,..., this study did not show a differential effect of spatial ability on navigation condition, the data did indicate that more research along these lines is warranted" (Antin et al., 1988). A single construct, therefore, is used to measure spatial ability in this study; spatial orientation will be tested using the Cube Comparisons Test.

IV. THEORIES OF INFORMATION PROCESSING RELATED TO ROUTE PRESENTATION AND GUIDANCE

Overview

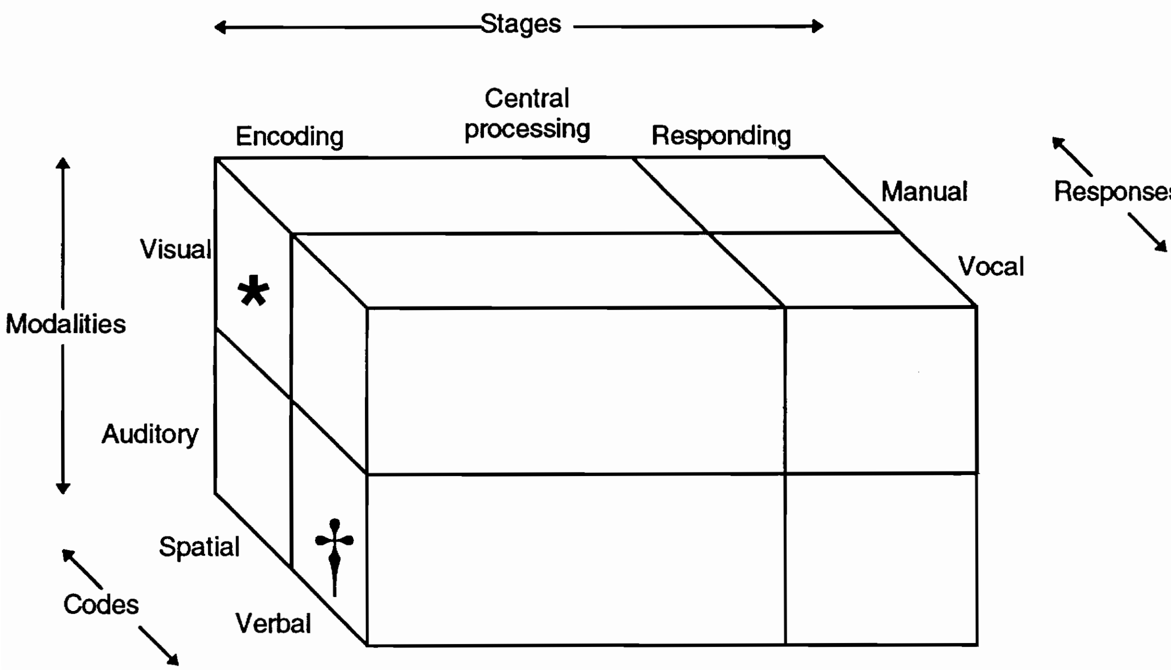
Green (1992) states that there have been few attempts to predict performance in navigation systems; predicted performance can be used by engineers to design better (more usable) systems. "There is a genuine lack of understanding of the mental processes involved in navigation" (Green, 1992). Aretz (1989) provides data for the development of a cognitive model of pilot flight navigation. He found that mental rotation is involved when attempting to align the orientation of the world reference frame (WRF) with the orientation of the ego reference frame (ERF). Also, he found a strong influence of significant individual differences. There are a few cognitive theories that will predict different outcomes for the optimal presentation of in-car route instructions (Verwey, 1989). The problem to be studied in this research is whether performance on navigation tasks can be predicted by cognitive theories. The cognitive theories that will be examined are the Multiple Resource Theory, Stimulus-Central Processing-Response Compatibility Theory, Recoding Mechanism Theory, and Dual-Coding Theory.

Multiple Resource Theory

The multiple resource view suggests that individuals have different capacities with resource properties rather than one single supply of undifferentiated resources. If more resources are shared, tasks will interfere more and performance trade-offs will be more likely to occur. Wickens (1992) defines resources along three dichotomous dimensions: two stage-defined resources (early versus late processes), two modality-defined resources (auditory versus visual encoding), and two resources defined by processing codes (spatial versus verbal). Figure 4 shows a proposed structure of processing resources. When two tasks demand separate rather than common resources on any of the three dimensions, time-sharing will be more efficient and changes in the difficulty of one task will be less likely to influence performance of the other. Each of the three dimensions that constitute the multiple-resource model are now described in detail.

The stages of the model include perceptual and central-processing activities (early processes) and responding activities (late processes) which are functionally separate. Evidence for this is shown when the difficulty of responding in a task is varied and this manipulation does not affect performance of a concurrent task whose demands are more perceptual (Wickens, 1992).

The perceptual modalities include visual and auditory modes. Sometimes it is easier for individuals to divide attention between the eye and ear than between two auditory channels or two visual channels, i.e., "cross-modal time-sharing is better than intramodal" (Wickens, 1992). Parkes and Coleman (1990) conducted a study to investigate methods of route guidance presentation while a participant was concurrently driving a simulated vehicle. They found that discrete route guidance presented auditorily was better than route guidance presented visually. Wickens, Sandry, and Vidulich (1983) found that tasks involving the retention of verbal information are best served by the auditory channel and tasks involving spatial localization and navigation by the verbal



* : **driving task (visual/spatial)**

† : **instructions (auditory/verbal)**

Figure 4. Proposed structure of processing resources (Wickens, 1992).

channel. Wickens (1980) discusses a number of other studies related to auditory versus visual encoding.

The processing codes include spatial and verbal codes. According to Polson and Friedman (1988), data indicate that spatial and verbal processes, or codes, whether functioning in perception, working memory, or response, depend on separate resources (Wickens, 1992). "The separation of spatial and verbal resources seemingly accounts for the high degree of efficiency with which manual and vocal outputs can be time-shared, assuming that manual responses are usually spatial in nature and vocal ones are verbal" (Wickens, 1992). Wickens, Sandry, and Vidulich (1983) carried out experiments to develop guidelines for synthesized auditory displays and speech recognizers in military aircraft. One experiment consisted of a simulated flight task which was performed concurrently with either a spatial task (target acquisition) or a verbal task (memory). They found that the best performance and least interference with the flight task were obtained when the spatial task was displayed visually and responded to manually and also when the verbal task was displayed auditorily and responded to with speech.

Multiple resource theory states that "tasks will interfere more and difficulty-performance trade-offs will be more likely to occur, if more resources are shared" (Wickens, 1992). Assuming that driving involves a control task which emphasizes the visual/spatial resources, this theory predicts that route instructions that are presented auditorily and verbally should be better than visual or spatial instructions since they minimize task interference.

Stimulus-Central Processing-Response Compatibility

The term stimulus-response compatibility describes the extent to which the ensemble of stimulus and response combinations comprising a task results in a high rate of information transfer (Simon, 1990). In other words, stimulus-response compatibility refers to the fact that some stimulus-response pairings are easier to use than others (Umiltá and Nicoletti, 1990). An important intermediary structure between the stimulus and the response is the operator's model of the system or the task (Eberts and Posey, 1990); this is also referred to as central processing. If a person has to compare the stimulus to something in memory, the processing will take more steps (Card, Moran, and Newell, 1983) and therefore, take more time. Figure 5 shows a simple stimulus-response analysis (Card, Moran, and Newell, 1983).

According to the Stimulus-Central Processing-Response compatibility theory of Wickens, Sandry, and Vidulich (1983), the compatibility depends on task type (verbal and spatial) that then is matched with the representation codes. They found that for tasks with a spatial representation code, the most compatible input was visual analog (an analog picture). Tasks relying on verbal codes are best served by auditory input, while those relying on spatial codes are better served by visual inputs (Wickens, Vidulich, and Sandry-Garza, 1984). To make an information display easier to comprehend, the design should minimize the difficulty of any recoding operations required of the user (Bartram, 1980).

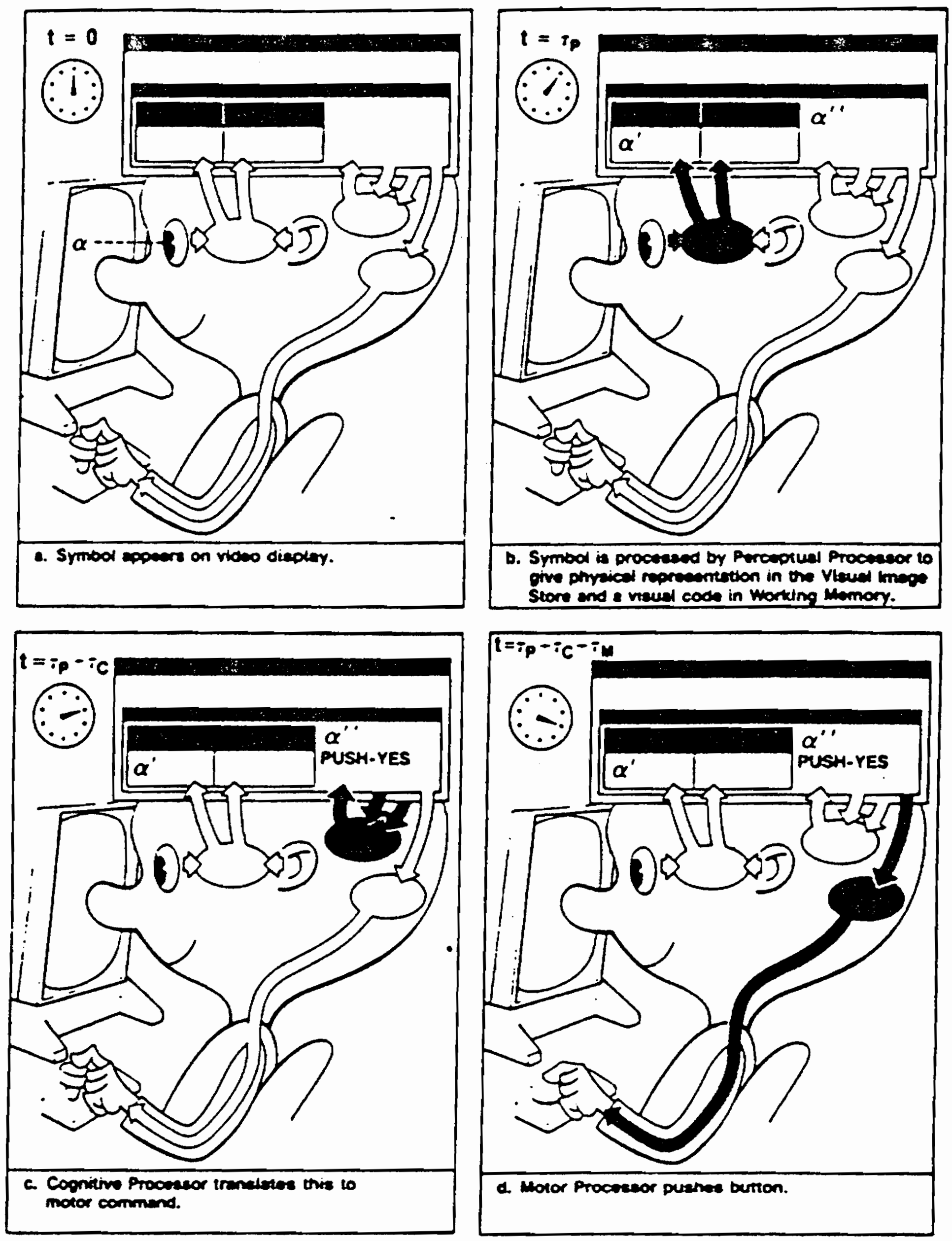


Figure 5. Simple stimulus-response analysis (Card, Moran, and Newell, 1983).

Compatible stimulus response relations will result in a high rate of information transfer (Fitts and Seeger, 1953).

Stimulus-central processing-response compatibility states that "information should be consistent with human expectations" (Verwey, 1989). This theory predicts that written navigational instructions would have to be transformed into an internal spatial network because the navigational task is spatial; therefore performance should be better when navigational information is presented in a visual/spatial format. This prediction is directly opposite of the next theory, the Recoding Mechanism theory. As stimulus-central processing-response compatibility effects only become apparent as task complexity increases (Bartram, 1980), there will be two levels of workload (high and low) used in the experiment investigating this theory.

Recoding Mechanism

Verbal recoding is the shift from a visual code to a verbal code. Working memory research and visual imagery studies show that auditory inputs automatically use a verbal code (Baddeley, 1986), while visual inputs automatically use a visual code (Kosslyn, 1980). This early visual coding "does not preclude the visual recoding of visually encoded material" (Brandimonte and Gerbino, 1993; see also Posner, 1969, Posner, Boies, Eichelman, and Taylor, 1969).

It is generally believed that verbal processing aids subsequent memory performance (Brandimonte, Hitch, and Bishop, 1992). A beneficial effect of verbal elaboration on memory performance has been reported for visual materials in various studies (Bartlett, Till, and Levy, 1980; Daniel and Ellis, 1972;

Ellis and Daniel, 1971). Meyers and Rhoades (1978) conducted four experiments investigating the way people coded various types of information and found a bias towards a verbal representation. Brandimonte, Hitch, and Bishop (1992) carried out experiments to test the hypothesis that verbal recoding of visual stimuli in short-term memory influences long-term memory encoding. They found that "whenever possible, subjects tend to use verbal recoding when memorizing a series of pictures" (Brandimonte et al., 1992).

The recoding mechanism assumes that "humans tend to translate pictoral information into a verbal memory code" (Verwey, 1989). This theory predicts that, if verbal recoding does take place with route instructions, verbal information would be preferred to spatial information since no translation is needed.

Dual Coding Theory

Dual coding theory is a general information processing theory that is supported by a large amount of empirical evidence (Paivio, 1986, 1991). This theory assumes that cognition is served by two functionally independent but partially interconnected symbolic systems, a verbal system that is specialized for dealing with linguistic stimuli and generating speech, and a nonverbal system specialized for dealing with nonverbal objects and events behaviorally as well as through the medium of imagery (Paivio, 1989). The basic framework of this theory proposes that information is coded and processed by separate verbal and nonverbal systems. The verbal system is specialized for handling language or speech, while the nonverbal system is specialized for coding and processing nonverbal material such as environmental sounds (not speech) and visual perceptions. The conceptual structure of the theory is hierarchical. At the highest level, sensory systems serve as cognitive mechanisms which represent or symbolize information. At the next level, two separate systems (verbal and nonverbal) are differentiated by their structural and functional properties. At the lowest level are the individual representational units called imagens (image generator) and logogens (word generator). These representational units are derived from experiences. A schematic depiction of the structure of verbal and nonverbal symbolic systems is shown in Figure 6. Cognitive activity can take place concurrently in both systems.

Dual coding theory proposes that information is coded and processed by separate verbal and nonverbal systems (Paivio, 1986), therefore presenting information both verbally and nonverbally will assist in the processing of that information. This theory predicts that optimal performance will occur if navigational information is presented both verbally and spatially.

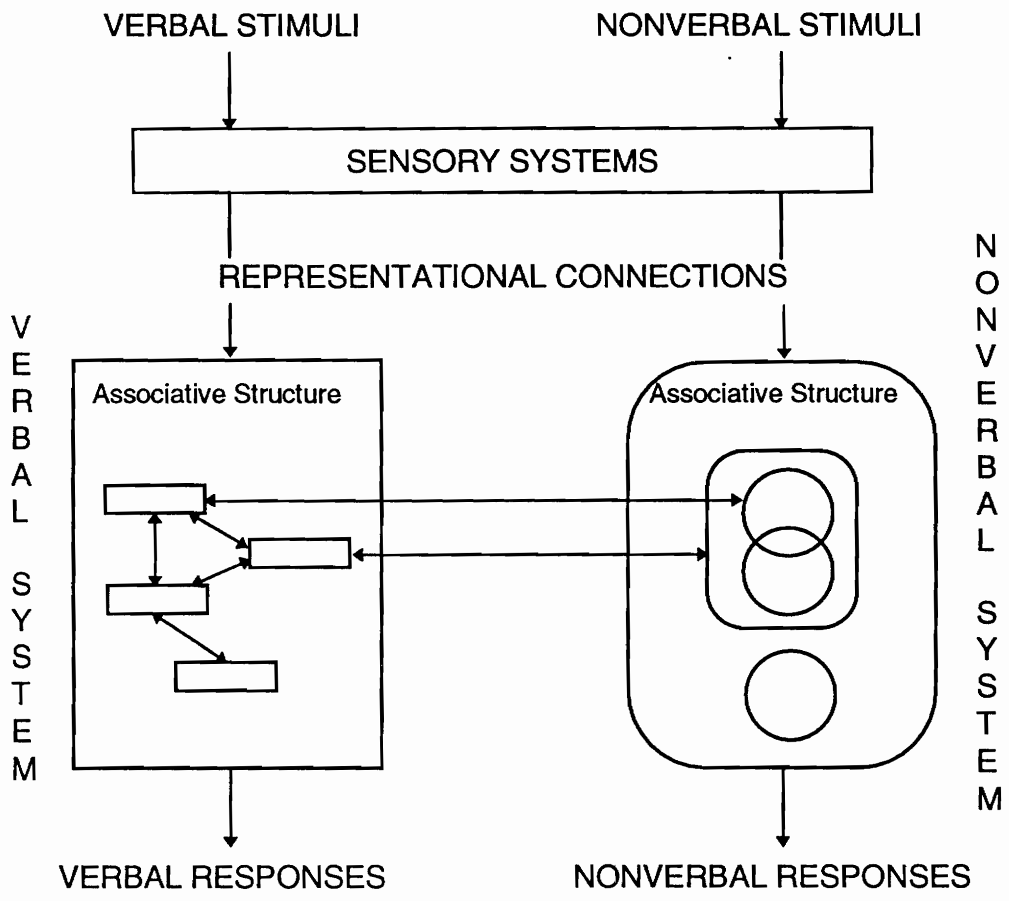


Figure 6. Schematic depiction of the structure of verbal and nonverbal symbolic systems (Paivio, 1986).

V. METHODOLOGY

Overview

The methodology employed in the laboratory experiment is reported in this chapter. The experiment was an investigation of four cognitive theories as related to navigational performance: Multiple Resource Theory, Stimulus-Central Processing-Response Compatibility Theory, Recoding Mechanism Theory, and Dual Coding Theory. The approach used to test the cognitive theories involved using a desktop virtual reality system to simulate an environment to maneuver through to a destination. This approach was used because it is generalizable to driving since the joystick is velocity controlled like the accelerator in an automobile. Also, a virtual reality system is quicker to program and less expensive to run than a driving simulator or an "on the road" vehicle. Navigation was examined; the actual task of driving was not analyzed, so using a maze for navigation was acceptable. The tasks were decision making tasks with no memory component. Once the scenario was finished it was not repeated, so many different scenarios were needed. The cost of carrying out this type of research in a driving simulator or "on the road" vehicle would have been excessive.

Subjects

There were 24 participants in the study. Verwey (1990) stated that gender differences have been found in workload assessment for driving so, for generalizability, he recommends using both male and female subjects. Wetherell (1981) found that performing a secondary task interfered with female driving ability, but not male driving ability and Hancock (1988, 1989) and Hancock, Rodenberg, Mathews, and Vercruyssen (1988) showed that females rated subjective workload higher than males. There were 12 males and 12 females in the study. Participants possessed a valid driver's license and had a (corrected) visual acuity of at least 20/40 with no color deficiencies. These were tested using Pseudo-Isochromatic Plates (for testing color perception) and Stereo Optical's OPTEC™ 2000 Vision Tester (for examining visual acuity). Visual acuity of 20/40 (corrected) was selected because it is the requirement for obtaining a driver's license. Color deficient individuals were screened out so there was no worry about people being able to discriminate information during the experiment because the display colors were fixed. Subjects were also screened for spatial ability. This was examined using the Cube Comparisons Test (Ekstrom et al., 1976). Those falling within the upper 25 percent (high spatial ability) and lower 25 percent (low spatial ability) participated in the experiment. These percentages were used because they were found to be reliable cutoffs for high and low spatial ability by Vicente (1987). The upper cutoff value was 34, so that anyone with a score of 34 or greater was placed in the high spatial ability group. The lower cutoff value was 18, so that anyone with a score of 18 or less was placed in the low spatial ability group. Upper and lower cutoff values were determined by analyzing the scores of 60 random people on the Cube Comparisons Test given by Neale (1995). Screening was done until half the males (6) and half the females (6) were found for each spatial ability group (high and low).

The data for one of the high spatial ability females had to be taken out of the study because she did not follow the task instructions. Her data were replaced by finding another female with high spatial ability.

Apparatus

This experiment took place in the Environmental and Safety Engineering Laboratory at Virginia Polytechnic Institute and State University. This laboratory is located in the Human Factors Engineering Center of the Department of Industrial and Systems Engineering. The software used in this study consisted of a computer program to simulate movement and present navigational information to the subject; Superscape VRT™ (a virtual reality software package) was used to program the environment.

The movement simulator part of the program was programmed to look like a maze. It required participants to start at one point and, with the help of navigational information, end at the desired destination. Virtual reality software allows the building of a virtual world, a "deliberately designed space in which objects 'live' through their relationships, under conditions specified by the world space they cohabit" (Jacobson, 1994). These worlds allow interaction between human cognition, such as mental maps, and the visual and auditory images produced by computers. The mazes were designed using a random maze generator written by John Lindal (1994); all mazes are shown in Appendix A. The random mazes were programmed into the 3-D movement simulator.

The navigational aid part presented the navigational information to the participant in a variety of ways: verbal (text-based) on the computer screen, spatial (graphic) on the computer screen, verbal (text-based) through speakers, or a combination of these. The programs were linked together and run on the same computer.

The hardware consisted of a WIN™ Pentium 90 Mz computer with a 17 in. SVGA monitor. It was equipped with a 3 button mouse and an Avenger™ 700 joystick, in addition to a Media Vision™ Pro Audio Studio 16 sound card and Aztech™ FX 20 amplified stereo speakers. The joystick was velocity controlled and the minimum velocity for the experiment was set at 250 units per frame update. The experimental set up is shown in Figure 7.

Task Description

The experiment consisted of 12 conditions which differed in workload level and type of navigational aid. For each condition subjects started traveling through the maze by following the instructions given by the navigational aid. Their destination was a red zone which, when entered, signified the end of that condition. Participants were encouraged to travel through the environment as quickly as possible, while minimizing the number of times they hit the walls. If participants deviated from the corridor they were supposed to be in, instructions were given in the text and voice aids to get them back on track. The map aid showed the whole path, so participants could see where they should be going and correct their own path. Figures 8 - 13 show each navigational aid. The voice navigational aid cannot be pictured for obvious reasons, but the mazes used for those conditions are shown in Figures 10, 12, and 13.

Experimental Design

The experimental design for the experiment was a four factor, mixed design as shown in Figure 14. There were four independent variables: gender, spatial ability, workload level, and navigational aid. Gender was a between-subject variable with two levels. Spatial ability was also a between-subject variable with two levels: high spatial ability (34 and above) and low spatial ability (18 and below). Workload level and navigational aid were within-subject

Figure 7. Experimental setup.

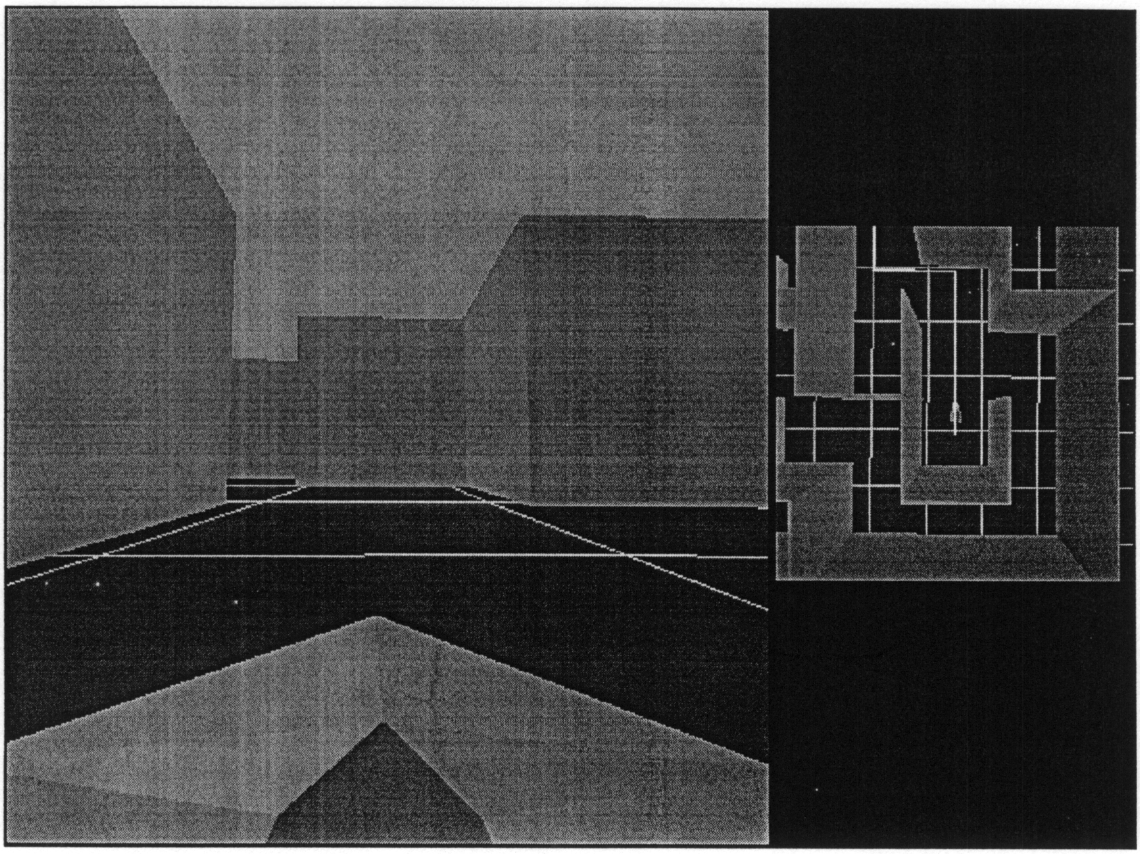


Figure 8. Maze and Map navigational aid.

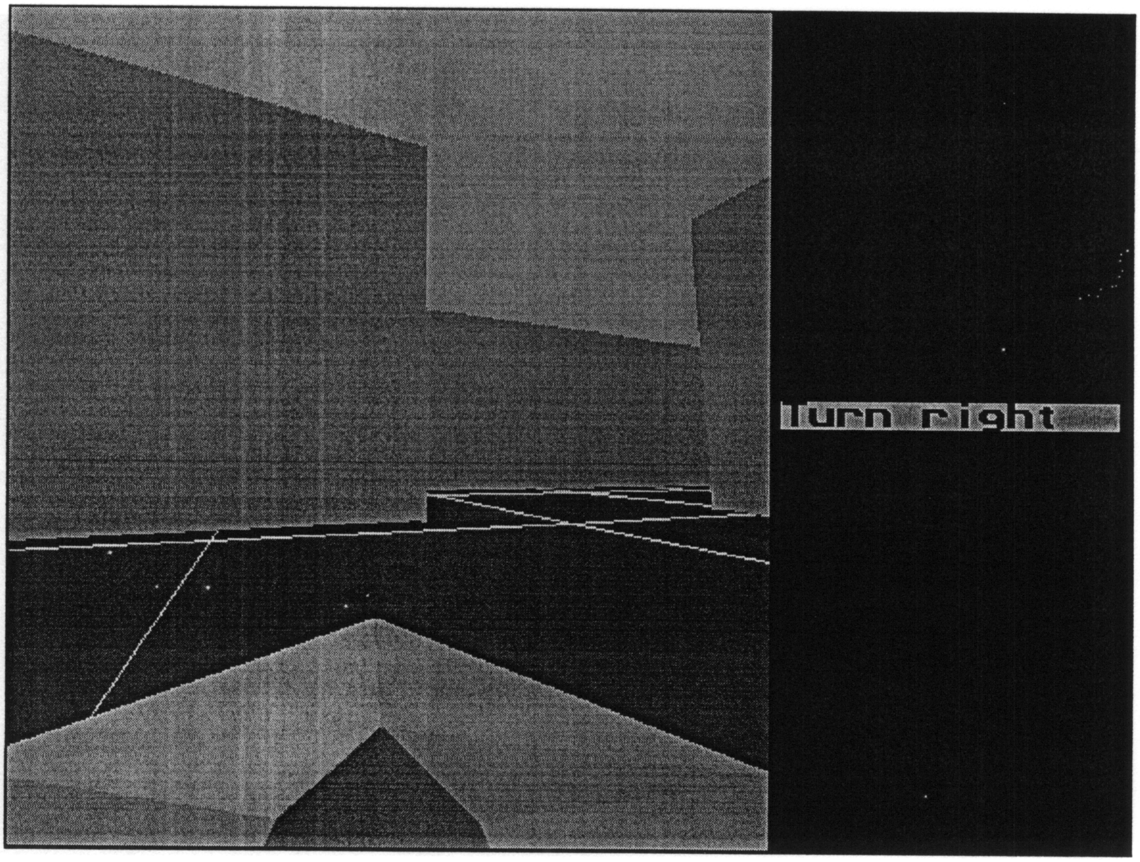


Figure 9. Maze and Text navigational aid.

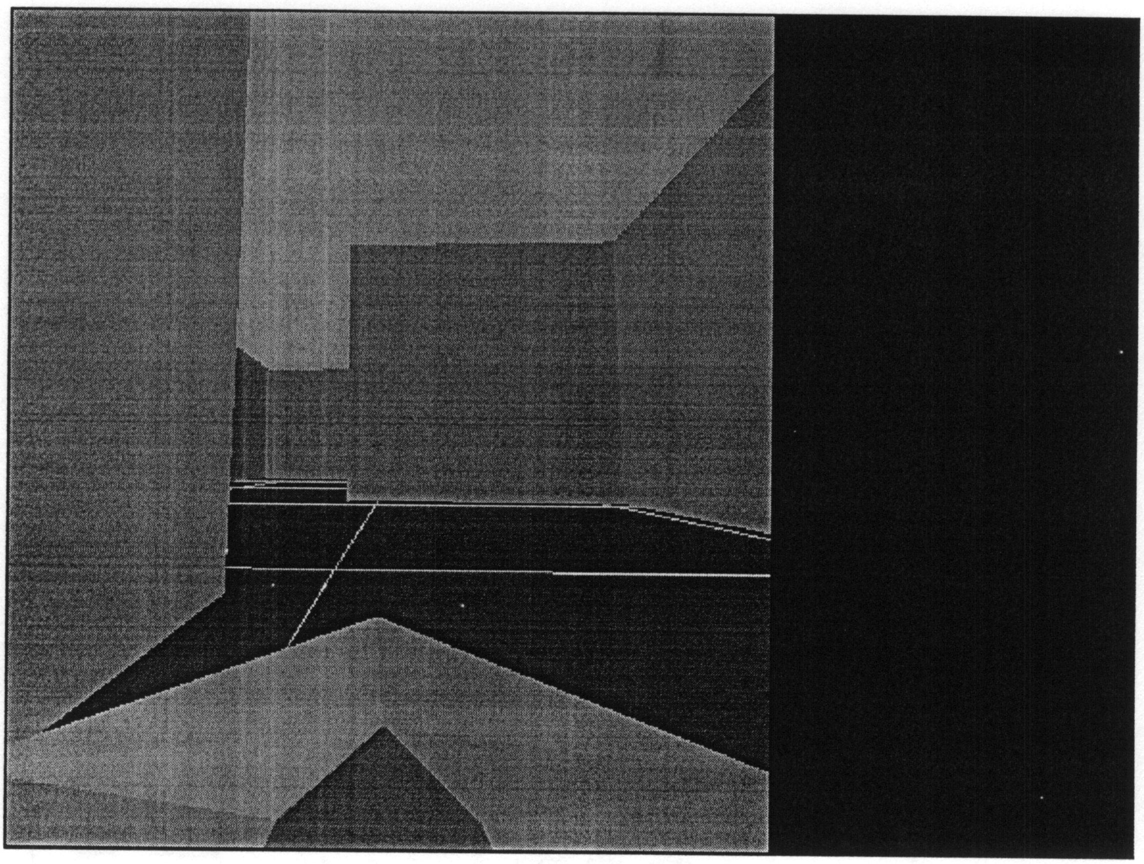


Figure 10. Maze and Voice navigational aid.

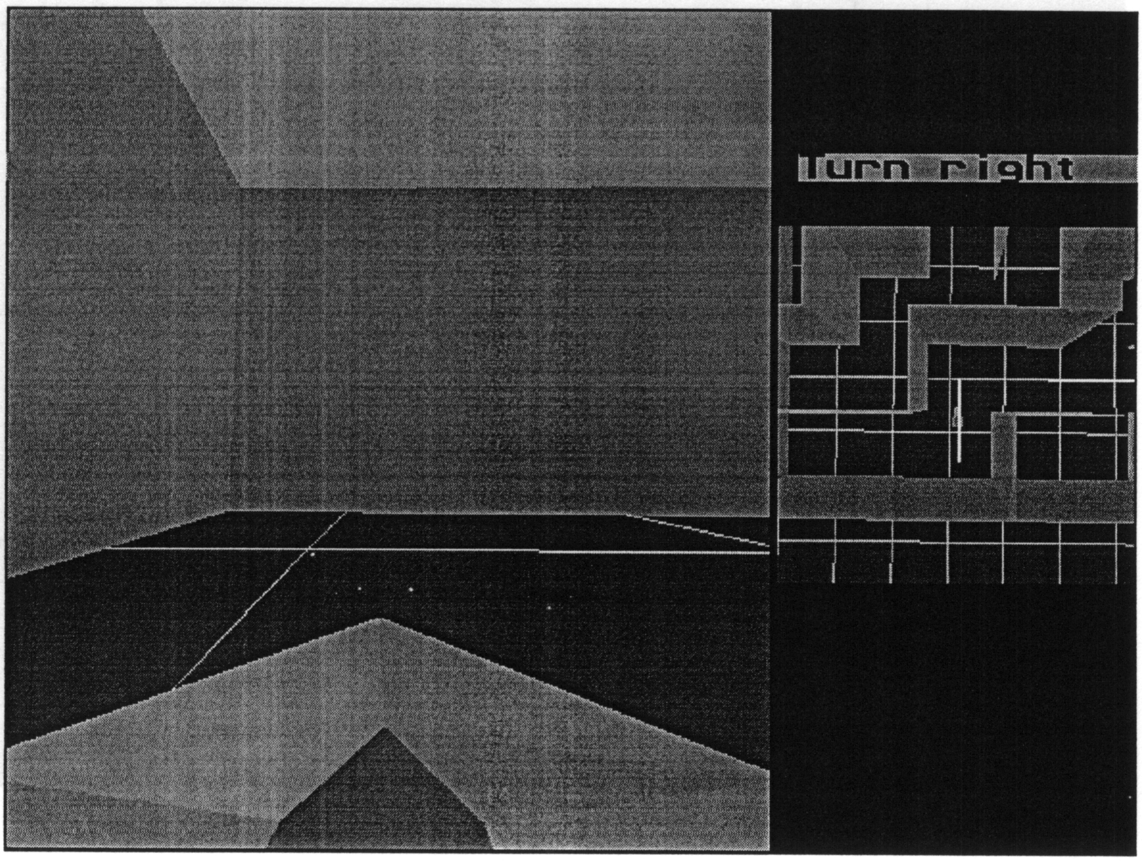


Figure 11. Maze and Map and Text navigational aids.

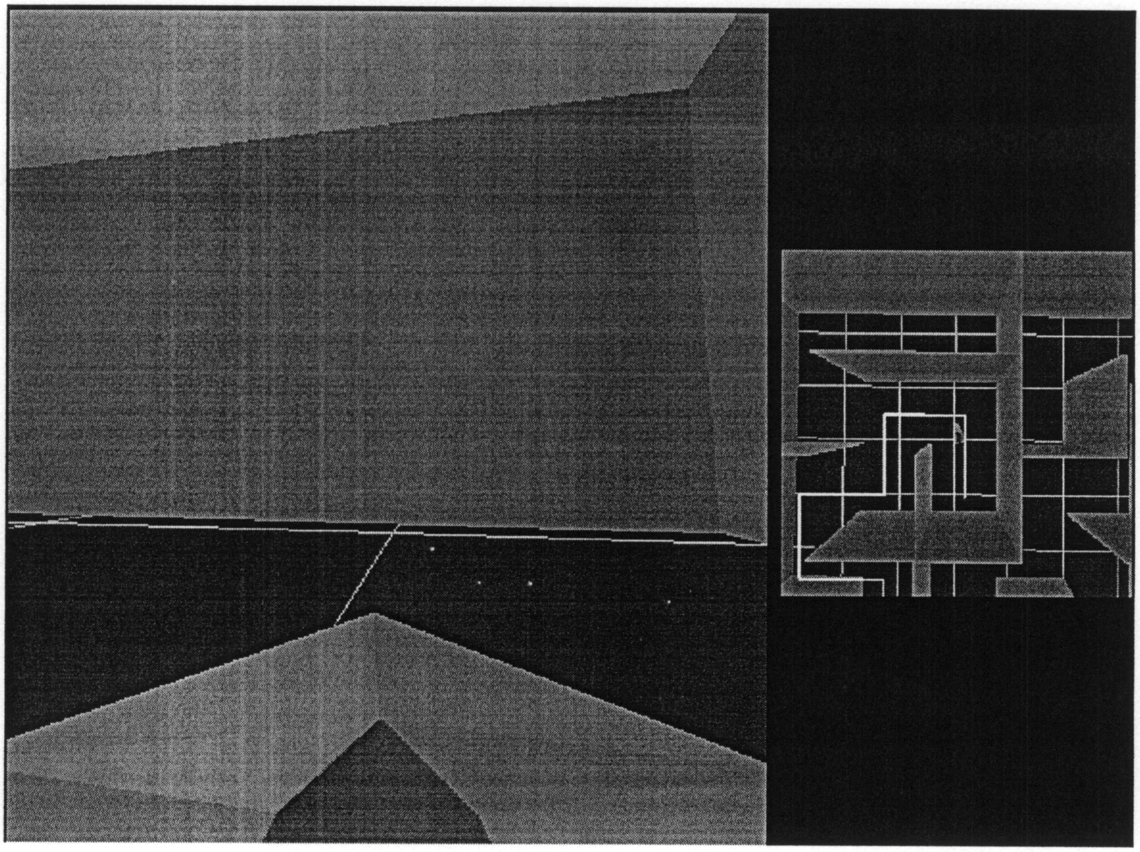


Figure 12. Maze and Map and Voice navigational aids.

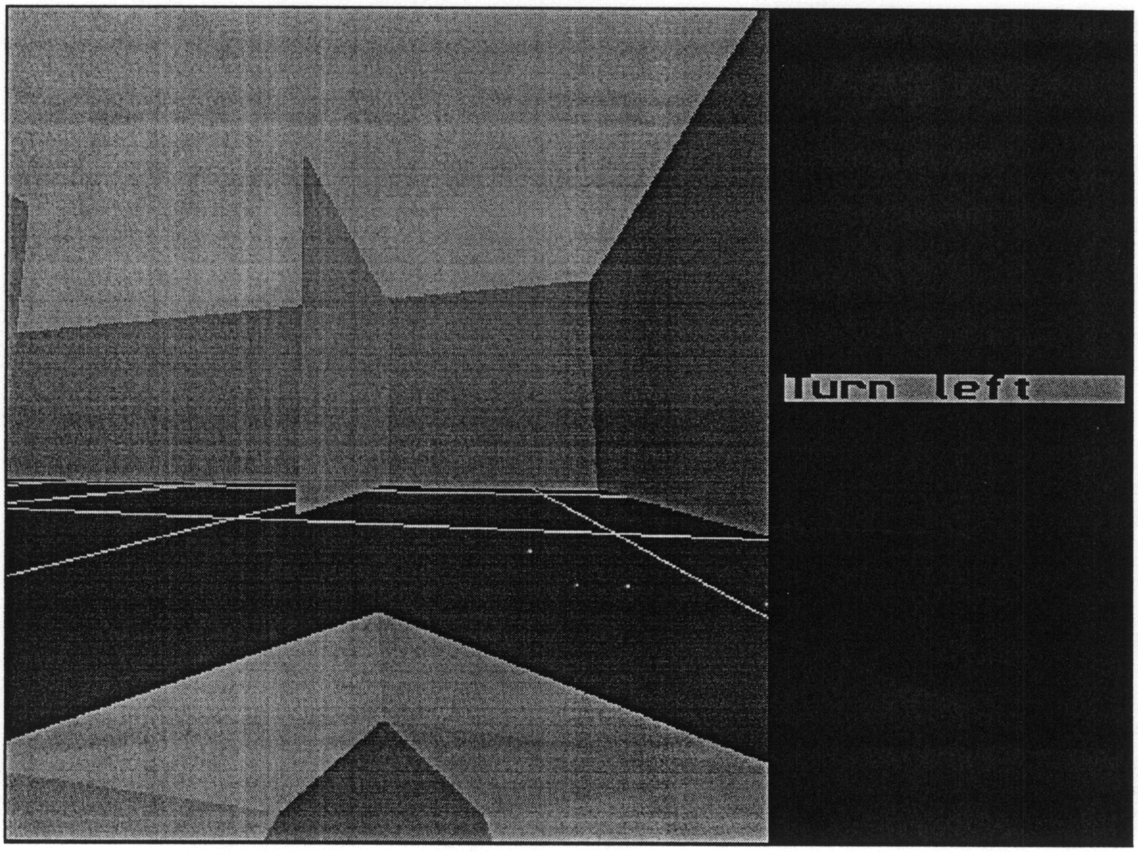


Figure 13. Maze and Text and Voice navigational aids.

Navigational Aid	Workload Level High	Workload Level Low
Visual/Verbal (text)	S_1- S_{24}	S_1- S_{24}
Auditory/Verbal (voice)	S_1- S_{24}	S_1- S_{24}
Visual/Spatial (map)	S_1- S_{24}	S_1- S_{24}
Visual/Verbal and Auditory/Verbal (text and voice)	S_1- S_{24}	S_1- S_{24}
Visual/Verbal and Visual/Spatial (text and map)	S_1- S_{24}	S_1- S_{24}
Auditory/Verbal and Visual/Spatial (voice and map)	S_1- S_{24}	S_1- S_{24}

24 Subjects:

Gender	Spatial Ability High	Spatial Ability Low
Female	S_{19}-S_{24}	S_{13}-S_{18}
Male	S_1-S_6	S_7-S_{12}

Figure 14. Experimental design.

variables. There were two levels of workload: low and high. A pilot study was conducted to test what difference in workload would be optimal; people had to notice some difference, but they also needed to be able to complete the task. If the workload levels were too similar, there would not be a noticeable difference; if the high workload level was too difficult, subjects would not be able to get through the maze. Five people tested various levels of the high workload condition and it was set at the following level. The low workload conditions were "smooth" conditions with no perturbations in position, while the high workload conditions employed a pseudorandom number generator to commence the rotation of the heading of the person in the maze. If the rotation occurred, there was a 75 percent probability that the person would rotate 4 degrees towards the right and a 25 percent chance that the rotation would be 7 degrees to the left. These perturbations in the high workload conditions required subjects to correct their heading to avoid inadvertently bumping into walls. There were six levels of navigational aid. Three of the levels were single conditions: map only, text only, and voice only. The other three conditions were dual conditions where navigational information was presented in two ways simultaneously: map and text, map and voice, and text and voice. The map conditions were presented in a north-up orientation. During pilot testing for map orientation subjects stated that the heading-up orientation changed too quickly and made them uncomfortable, so a north-up map orientation was used. All experimental conditions had predetermined routes for the subjects to follow; the navigation task was through unfamiliar territory. All experimental conditions were assigned using a Latin Square (Figure 15).

SUBJECT NUMBER

	1	2	3	4	5	6	7	8	9	10	11
	1	2	3	4	5	6	7	8	9	10	11
C	12	1	2	3	4	5	6	7	8	9	10
O	2	3	4	5	6	7	8	9	10	11	12
N	11	12	1	2	3	4	5	6	7	8	9
D	3	4	5	6	7	8	9	10	11	12	1
I	10	11	12	1	2	3	4	5	6	7	8
T	4	5	6	7	8	9	10	11	12	1	2
I	9	10	11	12	1	2	3	4	5	6	7
O	5	6	7	8	9	10	11	12	1	2	3
N	8	9	10	11	12	1	2	3	4	5	6
	6	7	8	9	10	11	12	1	2	3	4
	7	8	9	10	11	12	1	2	3	4	5

Figure 15. Latin Square for the order of treatment conditions.

The experiment tested the Multiple Resource Theory, Stimulus-Central Processing-Response Compatibility, Recoding Mechanism Theory, and Dual Coding Theory. Multiple resource theory predicted that auditory/verbal (voice) information presentation is best for navigational information in vehicles. Stimulus-central processing-response compatibility theory predicted that visual/spatial (map) information presentation is best for navigational information in vehicles. Recoding mechanism theory predicted that verbal (text or voice) information presentation is best for navigational information in vehicles. Dual coding theory predicted that the presentation of navigational information in vehicles should be both verbal and spatial at the same time (map and text or map and voice).

The dependent measures were number of wall hits, number of navigational errors, time to completion of task, subjective workload questionnaire scores, and subjective preference questionnaire scores. The task instructions told subjects that both speed and accuracy were important, so they needed to get to the destination as quickly as possible while bumping into as few walls as possible. Number of wall hits for the movement task was an objective measure of the subject's workload level. A wall hit was registered when the frame around the person in the maze touched the wall. The frame was invisible and did not extend beyond the person (it was "shrink wrapped" around the person); it allowed the person to move throughout the environment. There was no restitution when the person hit a wall so the person did not bounce off the wall like a bumper car. If the person hit the wall and continued to travel against the wall without separating from it, the number of wall hits was incremented by one only. But if the person hit the wall, moved away, and hit again, two wall hits were registered. The majority of wall hits seemed to occur while subjects were attempting to turn, so this was not a problem.

The number of errors made in navigation were recorded to check if there was a difference in navigational aids. A navigational error was defined as any deviation from the indicated path. The total maze was 10000 x 10000 units and each corridor was 1000 units wide. A person's location was tested using a 10 x 10 array of numbers where any deviation from the 1000 unit corridor was a navigational error. A turn around message was given at 100 units into an erroneous 1000 x 1000 unit block. Figure 16 shows an example of a navigation error.

The amount of time it took for the subjects to journey from their origin to their destination was noted to see if the navigational tools aided the participants in reaching their destination. The timer commenced after the variables were initialized during the execution of the virtual world (the maze). When the subjects entered the red zone, which was their destination, the clock stopped.

The subjective workload questionnaire scores showed if certain navigational aids were felt to be more mentally demanding than others. The Modified Cooper-Harper subjective workload questionnaire was used. Lower numbers on the scale indicate lower levels of workload, while higher numbers indicate greater levels.

The subjective preference questionnaire scores for each navigational tool indicated if participants preferred certain types of navigational information presentation. These preference scores were obtained by a paired comparison, administered via a questionnaire, of all navigational aids.

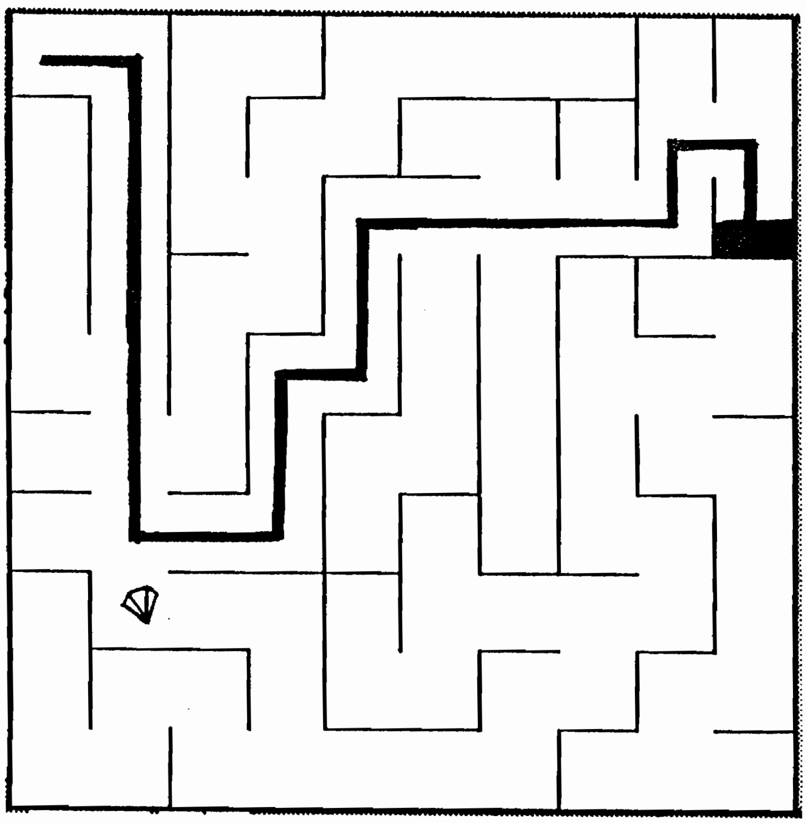


Figure 16. Example of a Navigation Error.

Protocol

The experiment was done during one experimental session lasting approximately two hours. The screening was done on a previous day. For the screening session, the participants read and signed a subject consent form (Appendix B). Next the screening was done for spatial ability, far visual acuity and color perception. Spatial ability was tested by the use of the Cube Comparisons Test (Appendix C). Subjects with at least 20/40 (corrected) vision, no color deficiency, and high or low spatial ability were scheduled to participate in the experiment at a later date. Those participants that did not qualify to continue with the experiment were paid $3 and thanked before leaving.

When the participants who continued with the experiment returned, they read the experimental instructions (Appendix D) and practiced with the movement simulator. There were three practice mazes that participants could go through as many times as they wished, until they felt they were comfortable with the experiment. Each of the practice mazes gave navigational information in one of the following ways: map, text, or voice. Afterward they started the experimental trials. There were 12 trials; there were two trials per navigational aid. Each trial consisted of one of the scenarios described above. After each scenario, subjects filled out the Modified Cooper-Harper subjective workload questionnaire for the condition they just completed (Appendix E). The instructions for this questionnaire are given in Appendix F. After all trials were completed, they filled out a subjective questionnaire on their preferences for the navigational aids (Appendix G). Participants were then paid $20 for their time and thanked before they left.

VI. RESULTS

Overview

A description of the statistical analyses and the results of these analyses performed on the experimental data are presented in this chapter. Discussion of these results is given in the next chapter. This chapter is organized into a description section and sections for each dependent variable (number of wall hits, number of navigational errors, time to complete task, subjective workload questionnaire scores and subjective preference questionnaire scores). Performance data (number of wall hits, number of navigation errors, and time to complete task) and subjective workload questionniare scores for all subjects are shown in Appendix H. The frequency of preference for each type of navigational aid was recorded for all subjects (Appendix I).

Data Analyses

Separate analyses of variance were done for each of the dependent variables (number of wall hits, number of navigational errors, time to complete task, subjective workload questionnaire scores, and subjective preference scores) for the experiment. The Greenhouse-Geisser correction factor (Winer, Brown, and Michels, 1991) was used when calculating the within subject (workload and navigational aid) values for the ANOVAs. This factor is a maximum correction for heterogeneity of covariance. When the unadjusted F value led to rejection of the null hypothesis and the Greenhouse-Geisser correction did not, the Huynh-Feldt correction for degrees of freedom was used

(Williges, 1993; Winer et al., 1991). This tests for overcorrection of the Greenhouse-Geisser correction factor. All reported *p*-values for within subject factors are Greenhouse-Geisser corrected, unless stated otherwise. Significant effects found in the ANOVAs were analyzed by a Newman-Keuls post hoc test to determine the exact differences.

Since the subjective preference questionnaire was a paired comparison of all tested navigational aids, the data were scaled before a one-way analysis of variance was performed. Thurstone's (1927) law of comparative judgment was used for the scaling. The law of comparative judgment consists of a "set of equations relating the proportion of times any given stimulus *k* is judged greater on a given attribute than any other stimulus *j* to the scale values and discriminal dispersion of the two stimuli on the psychological continuum" (Torgerson, 1958). The complete form of the law of comparative judgment is as follows:

$$S_1 - S_2 = x_{12}(\sigma_1^2 + \sigma_2^2 - 2r\sigma_1\sigma_2)^{1/2}$$

where: S_1, S_2 = the psychological scale values of the two compared stimuli,

x_{12} = the sigma value corresponding to the proportion of judgments $p_{1>2}$, When $p_{1>2}$ is greater than .50 the numerical value of x_{12} is positive. When $p_{1>2}$ is less than .50 the numerical value of x_{12} is positive.

σ_1, = discriminal dispersion of stimulus R_1,

σ_2 = discriminal dispersion of stimulus R_2,

r = correlation between the discriminal deviations of R_1 and R_2 in the same judgment.

This law is not solvable in its complete form because the number of unknowns is always greater than observable equations. Guilford (1954) and Gescheider

(1985) state the five "cases" (different ways of applying the law of comparative judgment) that Thurstone outlined. The present experiment fits into the fifth case:

$$S_1 - S_2 = x_{12}(2)^{1/2}$$

One of the assumptions made to reduce the complete law to the fifth case is that there is no correlation between the stimuli, which is the case when the stimulus series is very homogeneous. In more general terms, according to Guilford (1954), there is less likelihood of interaction of stimuli if they vary clearly in only one aspect. This is true; the only difference in the stimuli WAS the way the navigational information is presented. The second assumption is that the all the discriminal dispersions are equal. Guilford (1954) states that discriminal dispersions will be equal when stimuli are equally easy to place on a scale. There is no reason to believe that this is not true since the only difference in the stimuli is the way the information is being presented.

The frequency of preference for each of the mazes was recorded for each participant. The frequency data were then converted into a proportion matrix. Thurstone's scaling technique was then used to transform the proportion data into an interval scale. This was achieved by converting the proportion data in z-deviates of the normal distribution using Case 5 explained above. The mean z-values were then transferred to a scale on which the value of zero corresponds to the lowest mean z-deviate. In general, distances of interval scales have the property of additivity (Guilford, 1954). These data were then analyzed using a one-way analysis of variance with navigational aid being the single factor with six different levels (map only, text only, voice only, map and text, map and voice, text and voice).

Number of Wall Hits

The number of wall hits was used as a measure of performance on the primary task of maneuvering through the maze. A wall hit was registered when the frame around the person in the maze touched the wall. Increases in task difficulty or decreases in attention would increase the probability of the participant hitting the walls of the maze while moving through it.

The analysis of variance results for the number of wall hits are shown in Table 8. The main effect of Spatial Ability was the only significant factor (p = 0.0443) for this dependent variable. On average, participants with high spatial ability hit the walls less frequently ($\bar{x}$ = 1.167) than those with low spatial ability ($\bar{x}$ = 4.590). This effect is shown in Figure 17.

Number of Navigation Errors

The number of navigation errors was used as a measure of performance on the secondary task of navigating through the maze. A navigational error was defined as any deviation from the indicated path. Increases in the number of navigation errors indicate that the navigation information is not being presented in an effective way; people trying to extract information from the navigational aid are not able to in an efficient manner.

The analysis of variance results for the number of navigation errors are shown in Table 9. The main effects of Spatial Ability and Navigational Aid and the interaction of Navigational Aid×Spatial Ability were shown to be significant. On average (p = 0.0448), participants with low spatial ability committed more navigational errors ($\bar{x}$ = 0.993) than those with high spatial ability ($\bar{x}$ = 0.417), shown in Figure 18. Newman-Keuls post hoc analysis on the significant main

Table 8. ANOVA Summary Table for the Number of Wall Hits.

Source	df	Sum of Squares	Mean Square	F-Value	P-Value	G-G
Between Subjects						
Gender (G)	1	81.281	81.281	.444	.5130	
Spatial Ability (SA)	1	843.920	843.920	4.606	.0443	
G x SA	1	50.837	50.837	.277	.6042	
Subjects (S/G,SA)	20	3664.292	183.215			
Within Subjects						
Workload (WL)	1	251.253	251.253	3.210	.0883	.0883
WL x G	1	30.031	30.031	.384	.5426	.5426
WL x SA	1	222.253	222.253	2.840	.1075	.1075
WL x G x SA	1	25.087	25.087	.321	.5776	.5776
WL x S/G,SA	20	1565.292	78.265			
Nav. Aid (N)	5	956.976	191.395	2.107	.0707	.1586
N x G	5	660.448	132.090	1.454	.2116	.2446
N x SA	5	736.392	147.278	1.622	.1612	.2181
N x G x SA	5	553.976	110.795	1.220	.3054	.2888
N x S/G,SA	100	9082.125	90.821			
WL x N	5	356.142	71.228	.781	.5659	.4031
WL x N x G	5	366.198	73.240	.803	.5503	.3960
WL x N x SA	5	365.059	73.012	.800	.5521	.3968
WL x N x G x SA	5	367.059	73.412	.805	.5490	.3954
WL x N x S/G,SA	100	9124.125	91.241			

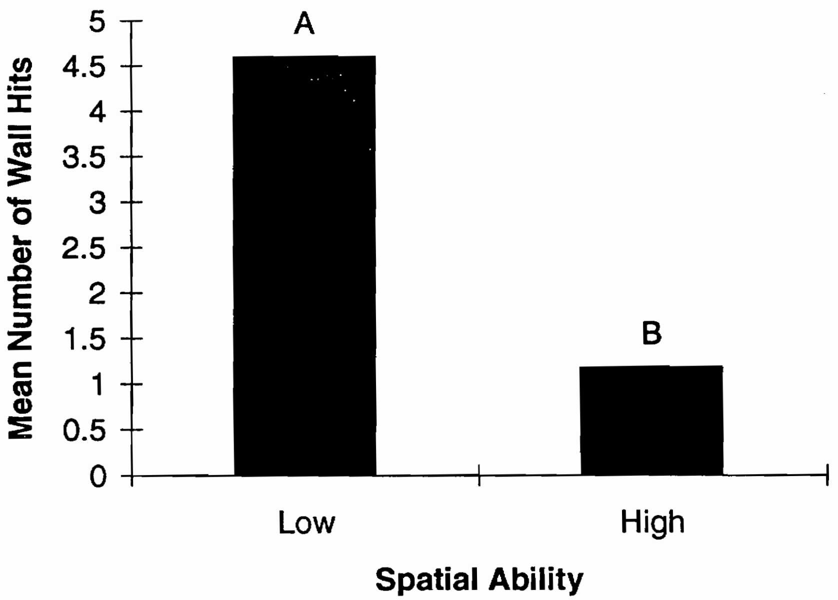


Figure 17. Main Effect of Spatial Ability for the Mean Number of Wall Hits (range was 0 - 161). (Means with the same letters are not significantly different.)

Table 9. ANOVA Summary Table for the Number of Navigation Errors.

Source	df	Sum of Squares	Mean Square	F-Value	P-Value	G-G	H-F
Between Subjects							
Gender (G)	1	8.337	8.337	1.597	.2209		
Spatial Ability (SA)	1	23.920	23.920	4.582	.0448		
G x SA	1	1.003	1.003	.192	.6658		
Subjects (S/G,SA)	20	104.403	5.220				
Within Subjects							
Workload (WL)	1	2.531	2.531	2.294	.1455	.1455	.1455
WL x G	1	.031	.031	.028	.8680	.8680	.8680
WL x SA	1	.087	.087	.079	.7820	.7820	.7820
WL x G x SA	1	.031	.031	.028	.8680	.8680	.8680
WL x S/G,SA	20	22.069	1.103				
Nav. Aid (N)	5	56.767	11.353	8.846	.0001	.0004	.0001
N x G	5	15.101	3.020	2.353	.0460	.1012	.0835
N x SA	5	19.601	3.920	3.054	.0131	.0519	.0370
N x G x SA	5	14.934	2.987	2.327	.0481	.1038	.0861
N x S/G,SA	100	128.347	1.283				
WL x N	5	14.990	2.998	2.215	.0586	.1080	.0882
WL x N x G	5	8.073	1.615	1.193	.3181	.3182	.3206
WL x N x SA	5	2.934	.587	.434	.8242	.6951	.7494
WL x N x G x SA	5	5.406	1.081	.799	.5530	.4806	.5101
WL x N x S/G,SA	100	135.347	1.353				

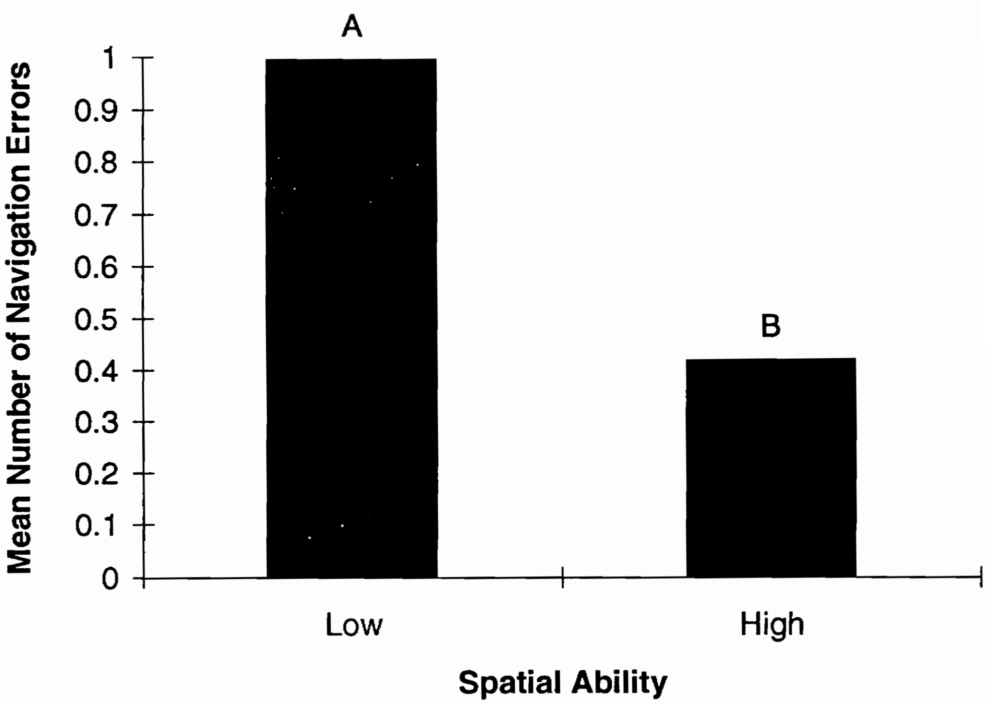


Figure 18. Main Effect of Spatial Ability for the Mean Number of Navigation Errors (range was 0 - 10). (Means with the same letters are not significantly different.)

effect of navigational aid ($p = 0.0004$) showed that significantly more navigational errors were made when using the map navigational aid than any other navigational aid (Table 10 and Figure 19). The unadjusted F value for the interaction between navigational aid and spatial ability indicated that there was a significant interaction ($p = 0.0131$), but Greenhouse-Geisser correction factor did not ($p = 0.0519$). The Huynh-Feldt correction for degrees of freedom was then used for the overcorrection of the Greenhouse-Geisser correction factor.

The Navigational Aid x Spatial ability interaction was shown to be significant ($p = 0.0370$, H-F correction). Newman-Keuls post hoc analysis on the interaction between navigational aid and spatial ability indicated that participants with low spatial ability had a more difficult time (more navigational errors) when navigating with the map but not with any other navigational aid (Table 11). The interaction is shown in Figure 20.

<u>Time to Complete Task</u>

The time to complete the task of maneuvering through the maze to the destination with different navigational aids was used as a measure of performance on the primary task of maneuvering. Increases in the time taken to complete the task indicate that the navigation information was not being presented in an efficient way. People trying to extract information from the navigational aid were not able to quickly get the information and respond to it; additional time was required to interpret the information.

The analysis of variance results for the time to complete the task are shown in Table 12. The main effect of Gender and the interaction of Workload and Navigational Aid were significant. On average ($p = 0.0092$) females took

Table 10. Means and Newman-Keuls Test Results for the Navigational Aid Main Effect for the Number of Navigation Errors. (Means with the same letters are not significantly different.)

Navigational Aid	Means	Range	N-K Grouping
Text and Voice	.312	0 - 10	A
Map and Voice	.333	0 - 4	A
Text	.500	0 - 7	A
Voice	.708	0 - 5	A
Map and Text	.750	0 - 4	A
Map	1.625	0 - 3	B

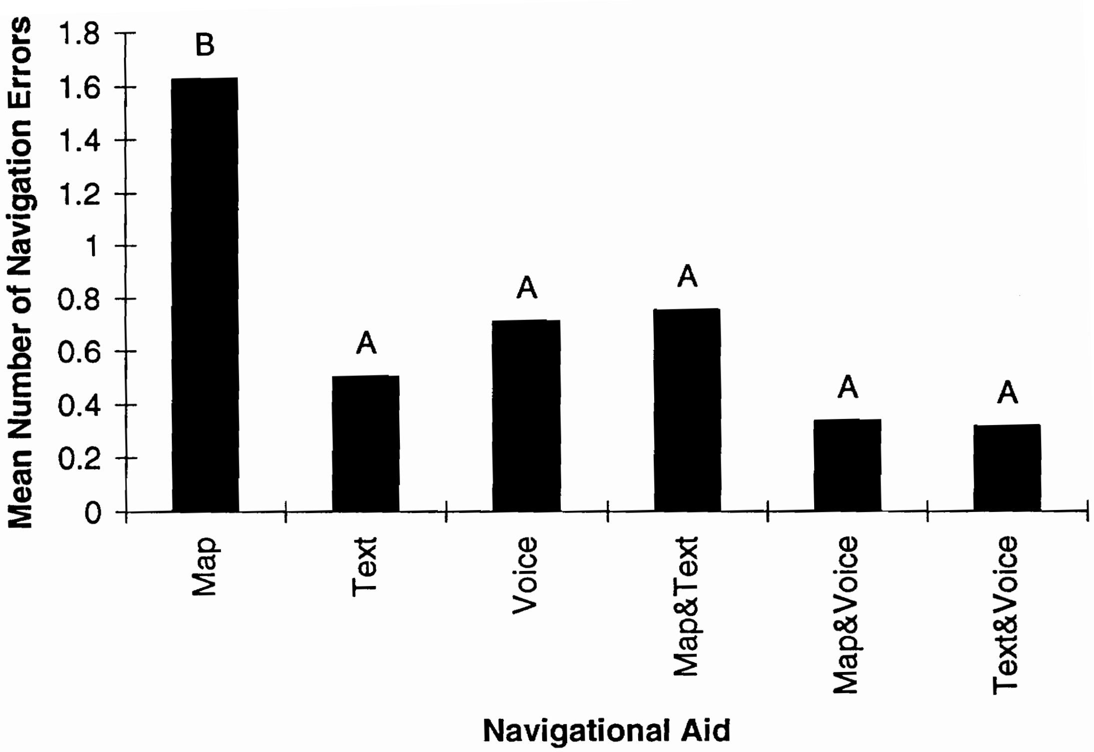


Figure 19. Main Effect of Navigational Aid for the Mean Number of Navigation Errors. (Means with the same letters are not significantly different.)

Table 11. Means and Newman-Keuls Test Results for the Navigational Aid x Spatial Ability Interaction for the Number of Navigation Errors. (Means with the same letters are not significantly different.)

Navigational Aid / Spatial Ability	Means	Range	N-K Grouping
Text and Voice/High	.167	0 - 1	A
Text/High	.250	0 - 1	A
Map and Voice/High	.292	0 - 4	A
Map and Voice/Low	.375	0 - 3	A
Map and Text/High	.417	0 - 3	A
Text and Voice/Low	.458	0 - 3	A
Voice/High	.583	0 - 7	A
Text/Low	.750	0 - 4	A
Map/High	.792	0 - 3	A
Voice/Low	.833	0 - 5	A
Map and Text/Low	1.083	0 - 5	A
Map/Low	2.458	0 - 10	B

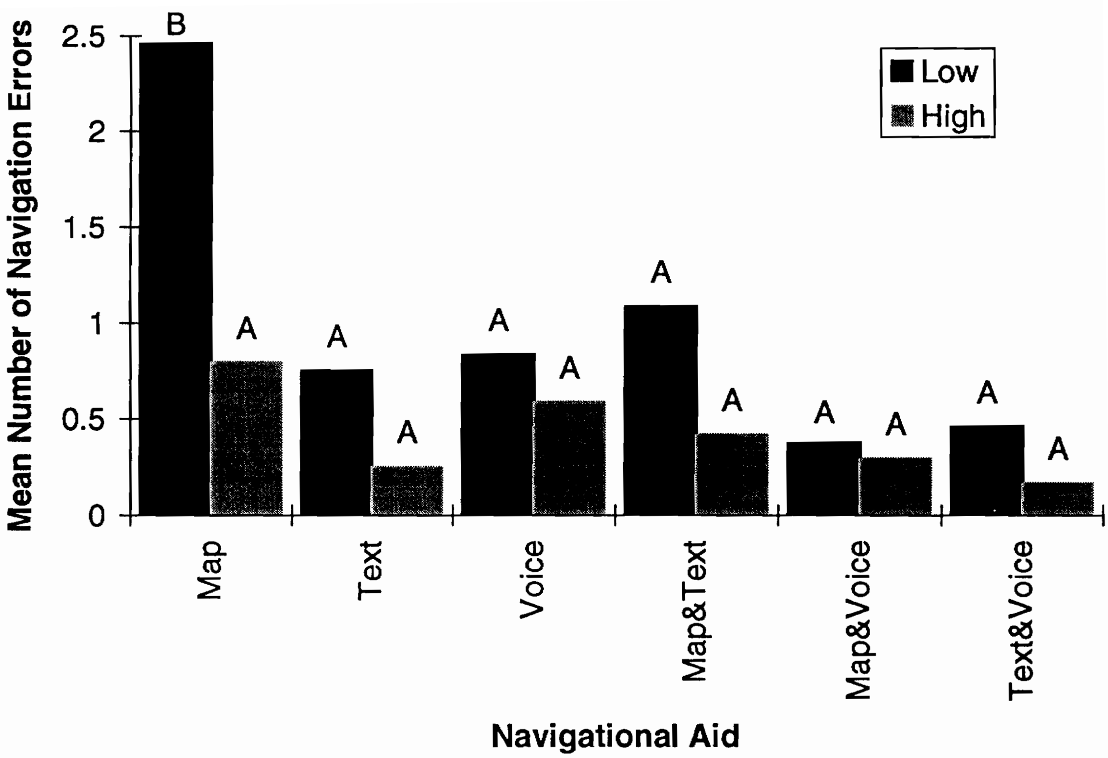


Figure 20. Navigational Aid x Spatial Ability (in legend) Interaction for the Mean Number of Navigation Errors. (Means with the same letters are not significantly different.)

Table 12. ANOVA Summary Table for the Time to Complete Task.

Source	df	Sum of Squares	Mean Square	F-Value	P-Value	G-G
Between Subjects						
Gender (G)	1	22366.125	22366.125	8.302	.0092	
Spatial Ability (SA)	1	9338.889	9338.889	3.467	.0774	
G x SA	1	1216.889	1216.889	.452	.5092	
Subjects (S/G,SA)	20	53879.972	2693.999			
Within Subjects						
Workload (WL)	1	470.222	470.222	1.514	.2329	.2329
WL x G	1	882.000	882.000	2.839	.1075	.1075
WL x SA	1	308.347	308.347	.993	.3310	.3310
WL x G x SA	1	.125	.125	.0004	.9842	.9842
WL x S/G,SA	20	6212.972	310.649			
Nav. Aid (N)	5	6074.042	1214.808	1.981	.0880	.1601
N x G	5	4794.958	958.992	1.564	.1773	.2255
N x SA	5	2781.694	556.339	.907	.4797	.3966
N x G x SA	5	1721.278	344.256	.561	.7294	.5442
N x S/G,SA	100	61333.028	613.330			
WL x N	5	16382.194	3276.439	7.576	.0001	.0033
WL x N x G	5	3775.333	755.067	1.746	.1311	.1941
WL x N x SA	5	196.486	39.297	.091	.9935	.8788
WL x N x G x SA	5	629.958	125.992	.291	.9168	.7066
WL x N x S/G,SA	100	43248.361	432.484			

longer ($\bar{x}$ = 67.083) to complete the task than males ($\bar{x}$ = 49.458), shown in Figure 21. Newman-Keuls post hoc analysis on the interaction between workload and navigational aid (Table 13) indicates ($p = 0.0033$) that the Text navigational aid (low workload condition), the Map and Voice navigational aids (low workload condition), the Map navigational aid (high workload condition), and the Voice navigational aid (high workload condition) took significantly less time to complete than the Map navigational aid (low workload condition), the Map and Text navigational aids (low workload condition), and the Text and Voice navigational aids (high workload condition). The time taken to complete the Voice navigational aid (low workload condition), the Text and Voice navigational aids (low workload condition), the Text navigational aid (high workload condition), the Map and Text navigational aids (high workload condition), and the Map and Voice navigational aids (high workload condition) were not significantly different than any other navigational aid. The interaction between Workload and Navigational Aid is shown in Figure 22.

Because time effects were anticipated, a second analysis of the time to complete task data was performed. One of the explanations for the absence of time effects was differences in the length of path travelled. An evaluation of the mazes created by the random maze generator indicated that the number of turns per maze were about equal (18 ± 4), but the distance travelled varied among conditions (220,000 - 420,000 maze units). The total times to complete task were normalized by dividing the total time by the required travel distance and these normalized times (seconds/10000 maze units) were analyzed by an ANOVA. The results are shown in Table 14. The main effects of Gender and Navigational Aid and the interactions of Navigational Aid x Gender and

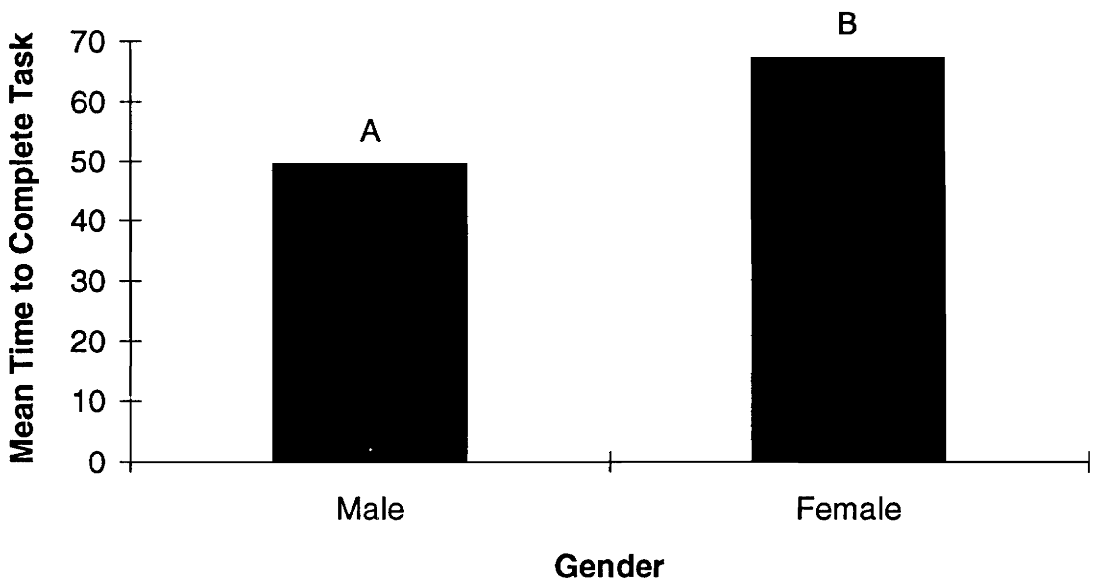


Figure 21. Main Effect of Gender for the Mean Time to Complete Task (seconds) (range is 25 - 306). (Means with the same letters are not significantly different.)

Table 13. Means and Newman-Keuls Test Results for the Workload x Navigational Aid Interaction for the Time to Complete Task (seconds). (Means with the same letters are not significantly different.)

Navigational Aid / Workload	Means	Range	N-K Grouping
Text/Low	46.375	33 - 71	A
Voice/High	47.375	34 - 129	A
Map and Voice/Low	48.083	34 - 72	A
Map/High	50.167	25 - 147	A
Text/High	55.917	40 - 98	A B
Map and Text/High	56.042	38 - 143	A B
Text and Voice/Low	57.208	41 - 86	A B
Map and Voice/High	62.875	43 - 92	A B
Voice/Low	63.042	34 - 306	A B
Text and Voice/High	69.583	47 - 137	B
Map and Text/Low	70.083	51 - 139	B
Map/Low	72.500	44 - 168	B

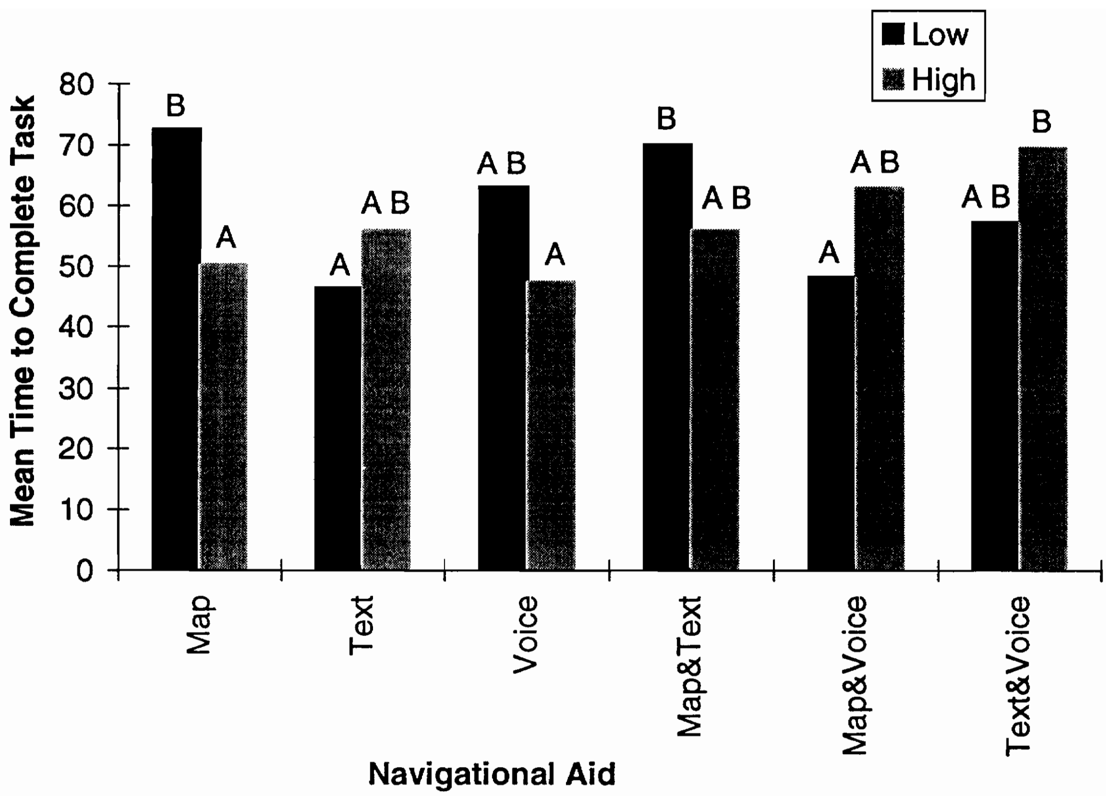


Figure 22. Workload (in legend) x Navigational Aid Interaction for the Mean Time to Complete Task (seconds). (Means with the same letters are not significantly different.)

Table 14. ANOVA Summary Table for Normalized Time to Complete Task.

Source	df	Sum of Squares	Mean Square	F-Value	P-Value	G-G
<u>Between Subjects</u>						
Gender (G)	1	21.429	21.429	8.580	0.0083	
Spatial Ability (SA)	1	10.215	10.215	4.090	0.0567	
G x SA	1	1.328	1.328	0.532	0.4743	
Subjects (S/G,SA)	20	49.953	2.498			
<u>Within Subjects</u>						
Workload (WL)	1	0.017	0.017	0.051	0.8234	0.8234
WL x G	1	0.266	0.266	0.782	0.3870	0.3870
WL x SA	1	0.036	0.036	0.104	0.7500	0.7500
WL x G x SA	1	0.137	0.137	0.402	0.5333	0.5333
WL x S/G,SA	20	6.813	0.341			
Nav. Aid (N)	5	27.356	5.471	13.931	0.0001	0.0001
N x G	5	7.643	1.529	3.892	0.0029	0.0341
N x SA	5	1.535	0.307	0.782	0.5651	0.4513
N x G x SA	5	1.042	0.208	0.530	0.7527	0.5719
N x S/G,SA	100	39.274	0.393			
WL x N	5	25.097	5.019	10.568	0.0001	0.0003
WL x N x G	5	0.184	0.037	0.078	0.9955	0.9131
WL x N x SA	5	3.148	0.630	1.326	0.2595	0.2766
WL x N x G x SA	5	1.973	0.395	0.831	0.5308	0.4354
WL x N x S/G,SA	100	47.497	0.475			

Workload x Navigational Aid were significant. On average ($p = 0.0083$) females had a longer normalized time ($\bar{x} = 2.108$) to complete the task than males ($\bar{x} = 1.563$), shown in Figure 23. Newman-Keuls post hoc analysis on the navigational aid main effect (Table 15 and Figure 24) indicates that the Text navigational aid, Map and Voice navigational aid and Text and Voice navigational aid required significantly less time than the Voice navigational aid and the Map and Text navigational aid. The Map navigational aid was not significantly different than any other condition. Newman-Keuls post hoc analysis on the interaction between gender and navigational aid (Table 16 and Figure 25) indicates that the Map and Text navigational aid required significantly more time for females than males. Newman-Keuls post hoc analysis on the interaction between workload and navigational aid (Table 17 and Figure 26) indicates that the Map and Text navigational aid (high workload condition) required significantly less time than all other navigational aids for both workload conditions, except the Voice navigational aids (high workload condition).

<u>Subjective Workload Questionnaire Scores</u>

The subjective workload questionnaire scores were used as a measure of the participant's impression of workload for each of the scenarios. Increases in the scores for subjective workload indicate that the participant perceived a navigational aid to be more mentally demanding to use than those which were scored lower. The Modified Cooper-Harper scale subjective workload questionnaire was used. Lower questionnaire scores indicate lower levels of workload, while higher scores indicate greater workload.

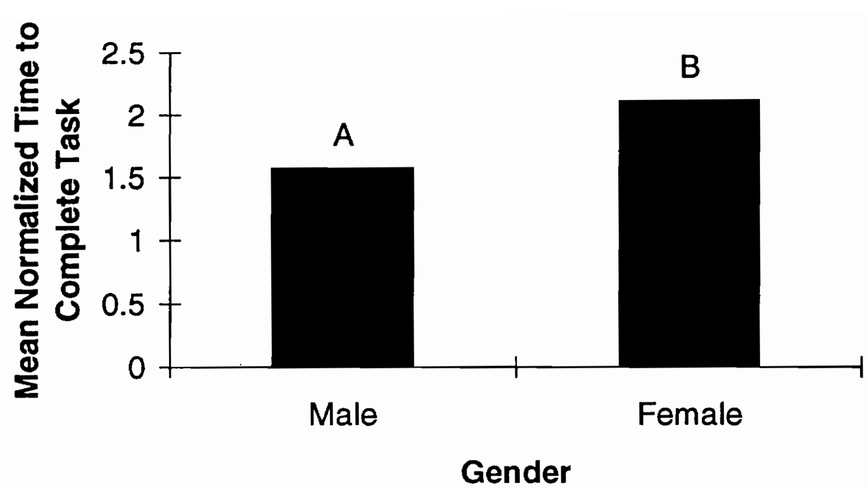


Figure 23. Main Effect of Gender for the Mean Normalized Time to Complete Task (seconds/10000 maze units). (Means with the same letters are not significantly different.)

Table 15. Means and Newman-Keuls Test Results for the Navigational Aid main effect for the Normalized Time to Complete Task (seconds/10000 maze units). (Means with the same letters are not significantly different.)

Navigational Aid	Means	Range	N-K Grouping
Map and Voice	1.477	0.81 - 4.74	A
Text and Voice	1.506	0.87 - 3.31	A
Text	1.688	1.21 - 2.97	A
Map	1.888	1.21 - 3.31	AB
Voice	2.209	1.31 - 4.93	B
Map and Text	2.247	0.92 - 8.27	B

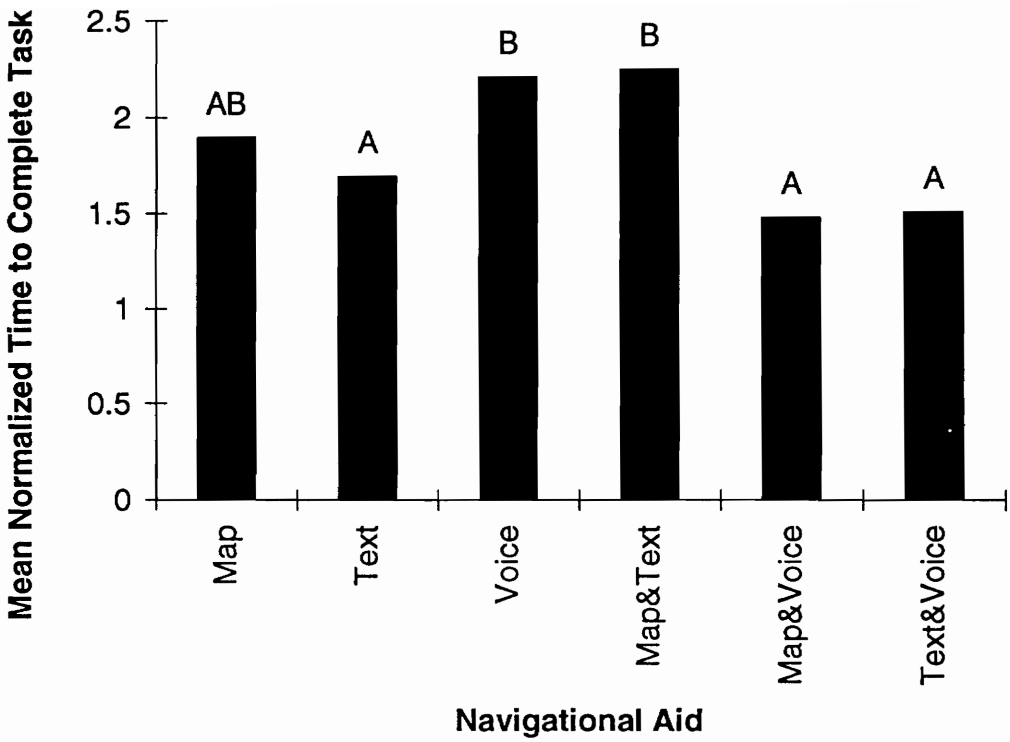


Figure 24. Main Effect of Navigational Aid for the Mean Normalized Time to Complete Task (seconds/10000 maze units). (Means with the same letters are not significantly different.)

Table 16. Means and Newman-Keuls Test Results for the Navigational Aid x Gender Interaction for the Normalized Time to Complete Task (seconds/10000 maze units). (Means with the same letters are not significantly different.)

Gender / Navigational Aid	Means	Range	N-K Grouping
Male/Map and Voice	1.233	1.31 - 4.28	A
Male/Text and Voice	1.292	0.87 - 1.44	A B
Male/Text	1.555	0.92 - 4.54	A B C
Male/Map and Text	1.617	1.21 - 2.53	A B C
Male/Map	1.682	1.21 - 1.93	A B C
Female/Map and Voice	1.720	1.41 - 6.46	A B C
Female/Text and Voice	1.721	1.03 - 3.31	A B C
Female/Text	1.820	1.05 - 8.27	B C
Male/Voice	1.998	0.81 - 3.42	C D
Female/Map	2.094	1.36 - 3.31	C D
Female/Voice	2.419	0.94 - 4.74	D
Female/Map and Text	2.876	1.26 - 3.23	E

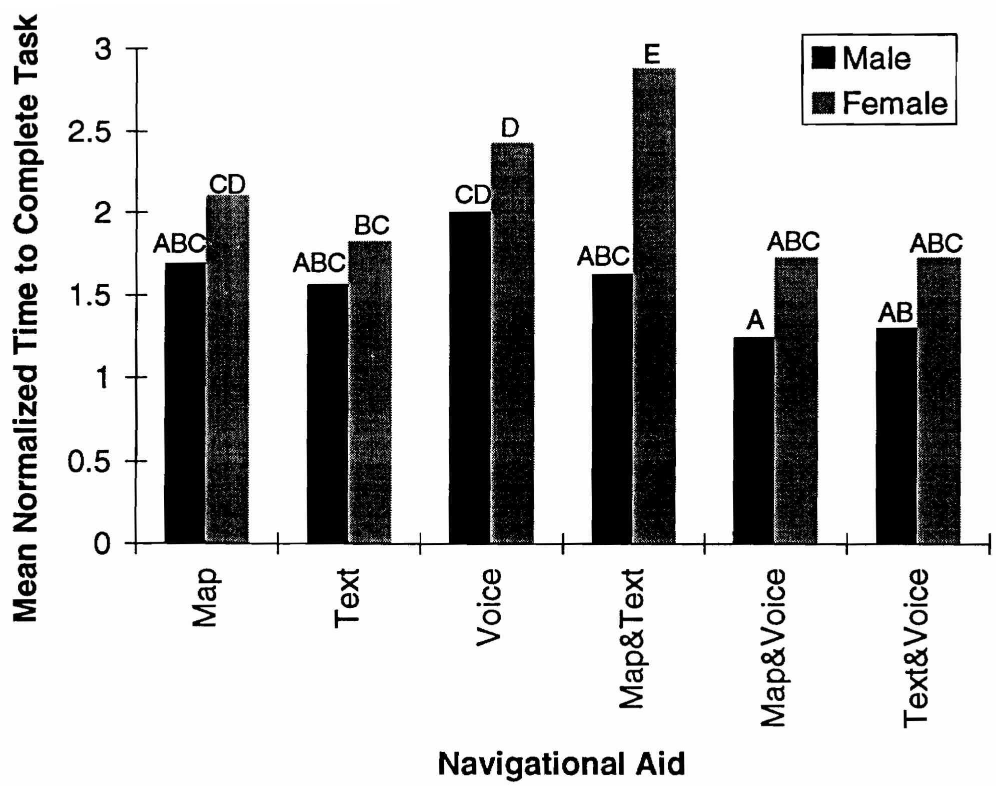


Figure 25. Navigational Aid x Gender (in legend) Interaction for the Mean Normalized Time to Complete Task (seconds/10000 maze units). (Means with the same letters are not significantly different.)

Table 17. Means and Newman-Keuls Test Results for the Workload x Navigational Aid Interaction for the Normalized Time to Complete Task (seconds/10000 maze units). (Means with the same letters are not significantly different.)

Navigational Aid / Workload	Means	Range	N-K Grouping
Text and Voice/High	1.215	0.87 - 3.31	A
Map and Voice/High	1.335	0.94 - 2.00	A B
Map and Voice/Low	1.418	0.81 - 4.74	A B C
Map/Low	1.668	1.21 - 3.31	A B C
Text/High	1.682	1.21 - 2.53	A B C
Text/Low	1.694	1.21 - 2.97	A B C
Map and Text/Low	1.705	0.92 - 8.27	A B C
Text and Voice/Low	1.798	1.23 - 2.63	A B C
Voice/High	1.932	1.31 - 4.93	B C
Map/High	2.107	1.50 - 3.23	C D
Voice/Low	2.485	1.68 - 4.89	D E
Map and Text/High	2.789	1.69 - 6.46	E

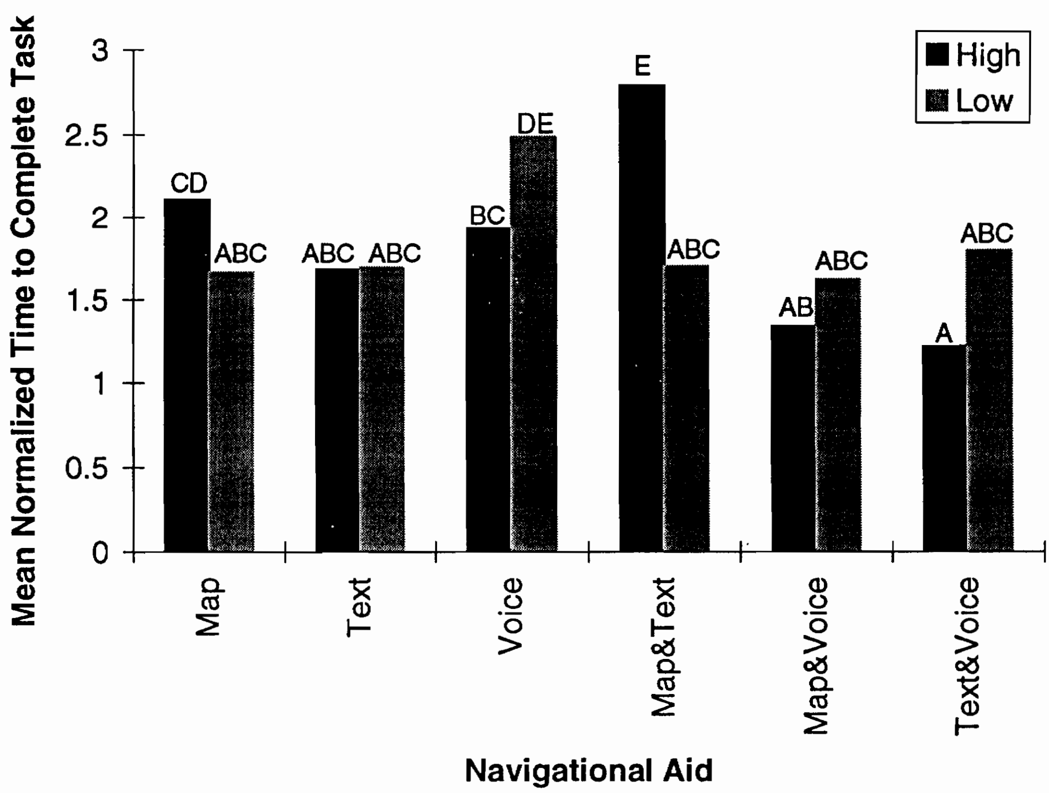


Figure 26. Workload (in legend) x Navigational Aid Interaction for the Mean Normalized Time to Complete Task (seconds/10000 maze units). (Means with the same letters are not significantly different.)

The analysis of variance results for the subjective workload questionnaire scores are shown in Table 18. The main effects of Workload and Navigational Aid and the interaction of Workload and Navigational Aid were significant. On average ($p = 0.0002$) participants rated the high workload conditions as requiring more mental effort ($\bar{x}$ = 3.583) than the low workload conditions ($\bar{x}$ = 2.653), shown in Figure 27. Newman-Keuls post hoc analysis on the significant main effect of Navigational Aid ($p = 0.0162$) indicates that there is little difference between the workload questionnaire scores for each of the navigational aids; none of the scores were found to be significantly different from one another (Table 19 and Figure 28). Newman-Keuls post hoc analysis on the Workload x Navigational Aid interaction ($p = 0.0020$) indicates there was a great deal of overlap with the workload ratings (Table 20). The exception is that the Text navigational aid (high workload condition) was rated to require significantly more mental effort than all the other scenarios. The interaction between Workload and Navigational Aid is shown in Figure 29.

A nonparametric analysis, Friedman's two-way analysis of variance by ranks, was also done on the subjective workload questionnaire scores. The results of this test were similar to the ANOVA; they were significant, F_r = 65.08156, $p < 0.001$.

Subjective Preference Questionnaire Scores

The subjective workload preference scores were used as a measure of the participant's partiality to certain navigational aids. They indicated if participants preferred certain types of navigational information presentation.

Table 18. ANOVA Summary Table for the Subjective Workload Questionnaire Scores.

Source	df	Sum of Squares	Mean Square	F-Value	P-Value	G-G
Between Subjects						
Gender (G)	1	.681	.681	.067	.7989	
Spatial Ability (SA)	1	.500	.500	.049	.8271	
G x SA	1	37.556	37.556	3.677	.0695	
Subjects (S/G,SA)	20	204.250	10.213			
Within Subjects						
Workload (WL)	1	62.347	62.347	21.530	.0002	.0002
WL x G	1	1.681	1.681	.580	.4551	.4551
WL x SA	1	4.500	4.500	1.554	.2270	.2270
WL x G x SA	1	10.889	10.889	3.760	.0667	.0667
WL x S/G,SA	20	57.917	2.896			
Nav. Aid (N)	5	47.528	9.506	4.189	.0017	.0162
N x G	5	17.361	3.472	1.530	.1872	.2246
N x SA	5	7.125	1.425	.628	.6788	.5639
N x G x SA	5	14.069	2.814	1.240	.2961	.3024
N x S/G,SA	100	226.917	2.269			
WL x N	5	35.194	7.039	5.256	.0003	.0020
WL x N x G	5	10.694	2.139	1.597	.1678	.1949
WL x N x SA	5	.792	.158	.118	.9881	.9586
WL x N x G x SA	5	4.069	.814	.608	.6941	.6265
WL x N x S/G,SA	100	133.917	1.339			

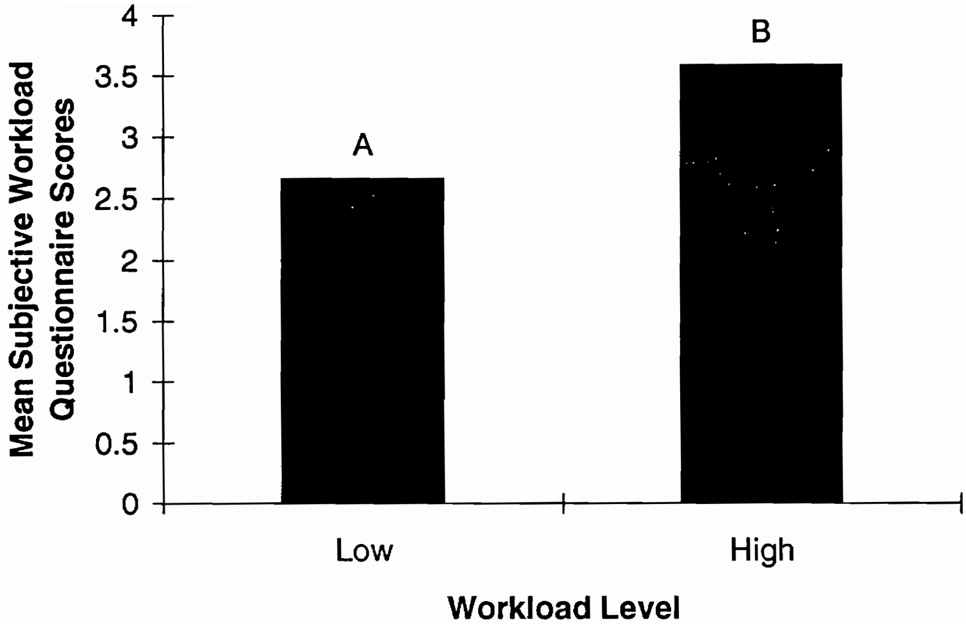


Figure 27. Main Effect of Workload for the Mean Subjective Workload Questionnaire Scores. Lower numbers indicate less workload. (Means with the same letters are not significantly different.)

Table 19. Means and Newman-Keuls Test Results for the Navigational Aid Main Effect for the Subjective Workload Questionnaire Scores. Lower numbers indicate less workload. (Means with the same letters are not significantly different.)

Navigational Aid	Means	Range	N-K Grouping
Map and Voice	2.375	1 - 7	A
Text and Voice	2.938	1 - 8	A
Map and Text	3.104	1 - 8	A
Voice	3.167	1 - 10	A
Map	3.500	1 - 9	A
Text	3.625	1 - 9	A

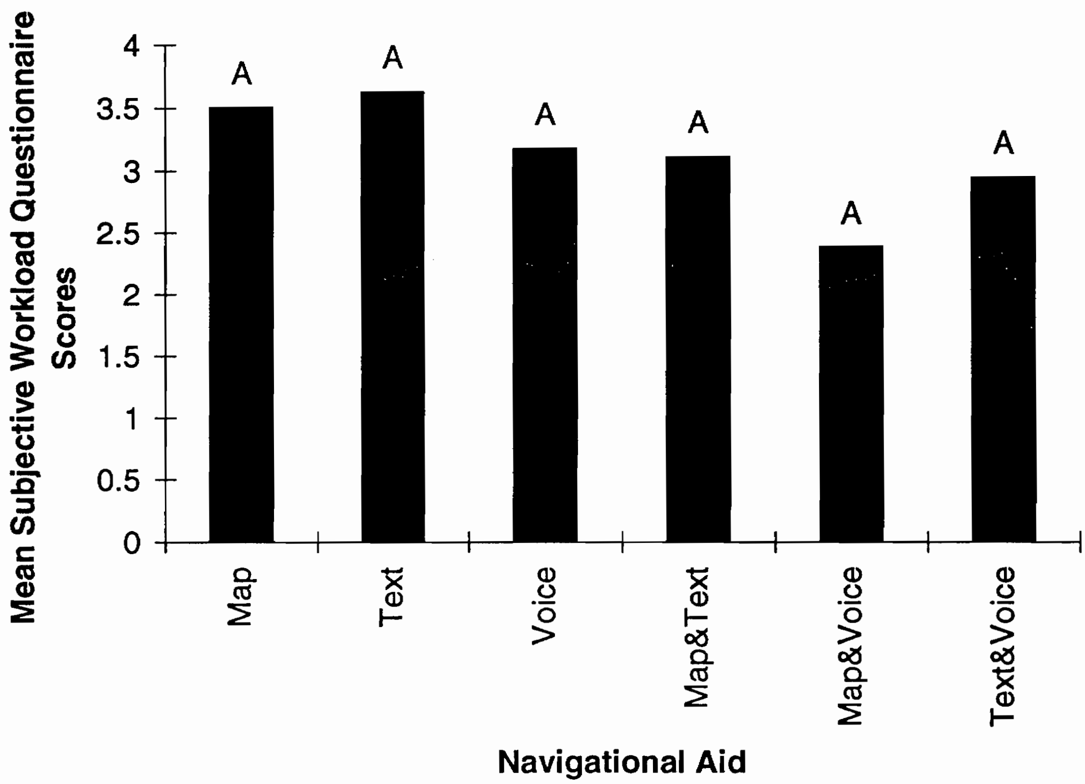


Figure 28. Main Effect of Navigational Aid for the Mean Subjective Workload Questionnaire Scores. Lower numbers indicate less workload. (Means with the same letters are not significantly different.)

Table 20. Means and Newman-Keuls Test Results for the Workload x Navigational Aid Interaction for the Subjective Workload Questionnaire Scores. Lower numbers indicate less workload. (Means with the same letters are not significantly different.)

Navigational Aid / Workload	Means	Range	N-K Grouping
Map and Voice/Low	1.833	1 - 3	A
Text and Voice/Low	2.208	1 - 4	A B
Text/Low	2.625	1 - 5	A B C
Map and Text/Low	2.708	1 - 5	B C D
Map and Voice/High	2.917	1 - 7	B C D
Voice/High	3.083	1 - 6	B C D
Voice/Low	3.250	1 - 10	C D
Map/Low	3.292	1 - 9	C D
Map and Text/High	3.500	1 - 8	C D
Text and Voice/High	3.667	1 - 8	D
Map/High	3.708	1 - 9	D
Text/High	4.625	1 - 9	E

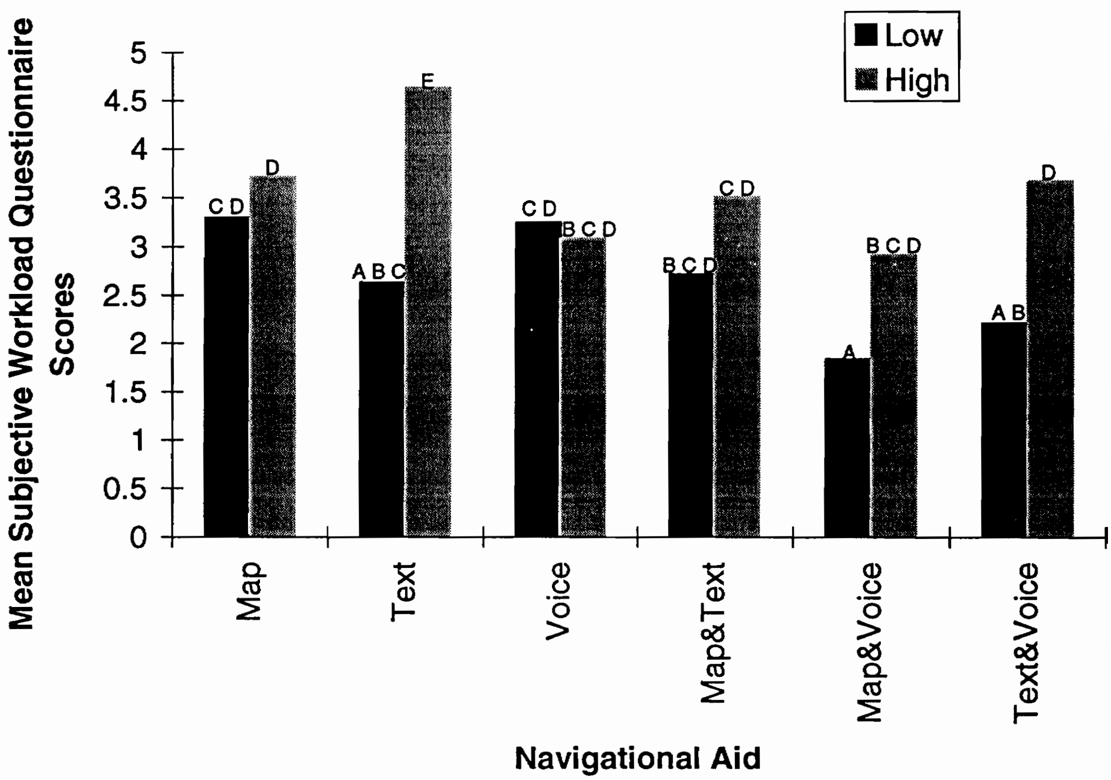


Figure 29. Workload (in legend) x Navigational Aid Interaction for the Mean Subjective Workload Questionnaire Scores. Lower numbers indicate less workload. (Means with the same letters are not significantly different.)

After completing all conditions the subjects did a pair comparison of the navigational aids. The preference data were scaled using Thurstone's (1927) law of comparative judgment. Increases in the scaled percentage data for subjective preference indicate that the participant preferred one type of navigational information presentation over another. The scaled vaues for all subjects along with the results of the Newman-Kuels post hoc test are shown in Table 21. The scaled values were checked for additivity by comparing the statistic, $X^2 = fns^2$ ($f = 1/2(k-1)(k-2)$ degrees of freedom), to the chi-squared distribution. The results of this test gave 6.0240 which is not significant ($\alpha = 0.05$) when compared with the chi-squared vale for 10 df ($X^2 = 18.3$). This result indicates that the scale possesses additivity and the usual analysis can be done. The ANOVA produced significant results ($\alpha = 0.05$) indicating that subjects could discriminate among the six types of navigational aids. The ANOVA summary table is presented in Table 22.

Analyses of variance were performed on the preference data for females and males; high and low spatial ability subjects; and high spatial ability females, low spatial ability females, high spatial ability males, and low spatial ability males. Significant differences were found ($\alpha = 0.05$) for females, low spatial ability subjects, low spatial ability females, and high spatial ability males. In all cases, the navigational aid employing both a map and text was found to be the most preferred navigational aid; for females, text and voice, and for low spatial ability females, map and voice navigational aids were tied with the map and text display for most preferred navigational aid. Tables 23, 25, 26, 27, 29, 30, 32, and 34 show the scale values and, if necessary, the Newman-Kuels post hoc test grouping and Tables 24, 28, 31, and 33 show the significant analyses of variance results.

Table 21. Results of Thurstone's Scaling Procedure and Newman-Kuels post hoc test results on the Frequency of Preference Data for the Navigational Aids for all subjects. (Scaled values with the same letters are not significantly different.)

Condition	Navigational Aid	Frequency of Preference	Scaled value	N-K Test
4	Map and Text	102	2.0421	A
5	Map and Voice	67	0.9392	B
6	Text and Voice	63	0.8034	B
2	Text	54	0.5716	C
1	Map	41	0.1302	D
3	Voice	33	0.0000	D

Table 22. ANOVA Summary Table for the Subjective Preference Questionnaire Scores for all participants.

Source	df	Sum of Squares	Mean Square	F-Value*
Between Navigational Aids	5	16.1193	3.2239	32.1106
Residual	10	1.0038	0.1004	
Total	15	17.1231		

* $p < 0.001$

Table 23. Results of Thurstone's Scaling Procedure and Newman-Kuels post hoc test results on the Frequency of Preference Data for the Navigational Aids for Female subjects. (Scaled values with the same letters are not significantly different.)

Condition	Navigational Aid	Frequency of Preference	Scaled value	N-K Test
4	Map and Text	48	3.7173	A
5	Map and Voice	35	2.0916	B
6	Text and Voice	33	1.9246	AB
2	Text	27	1.6168	B
3	Voice	21	1.2905	B
1	Map	16	0.0000	B

Table 24. ANOVA Summary Table for the Subjective Preference Questionnaire Scores for Female participants.

Source	df	Sum of Squares	Mean Square	F-Value*
Between Navigational Aids	5	43.83383	8.7668	3.3331
Residual	10	26.3019	2.6302	
Total	15	70.1357		

* $p = 0.0499$

Table 25. Results of Thurstone's Scaling Procedure on the Frequency of Preference Data for the Navigational Aids for Male subjects.

Condition	Navigational Aid	Frequency of Preference	Scaled value
4	Map and Text	54	3.5163
5	Map and Voice	32	1.2500
2	Text	27	0.8586
1	Map	25	0.7594
6	Text and Voice	30	0.1139
3	Voice	12	0.0000

Table 26. Results of Thurstone's Scaling Procedure on the Frequency of Preference Data for the Navigational Aids for subjects with High Spatial Ability.

Condition	Navigational Aid	Frequency of Preference	Scaled value
4	Map and Text	49	3.4706
5	Map and Voice	35	1.7237
6	Text and Voice	34	1.6607
2	Text	25	1.1995
3	Voice	21	0.6915
1	Map	16	0.0000

Table 27. Results of Thurstone's Scaling Procedure and Newman-Kuels post hoc test results on the Frequency of Preference Data for the Navigational Aids for subjects with Low Spatial Ability. (Scaled values with the same letters are not significantly different.)

Condition	Navigational Aid	Frequency of Preference	Scaled value	N-K Test
4	Map and Text	53	2.1910	A
5	Map and Voice	32	0.8664	B
6	Text and Voice	29	0.6801	BC
2	Text	29	0.6318	C
1	Map	20	0.1729	D
3	Voice	17	0.0000	D

Table 28. ANOVA Summary Table for the Subjective Preference Questionnaire Scores for participants with Low Spatial Ability.

Source	df	Sum of Squares	Mean Square	F-Value*
Between Navigational Aids	5	18.02516	3.605	36.5993
Residual	10	0.9852	0.0985	
Total	15	19.0104		

* $p < 0.001$

Table 29. Results of Thurstone's Scaling Procedure on the Frequency of Preference Data for the Navigational Aids for Female subjects with High Spatial Ability.

Condition	Navigational Aid	Frequency of Preference	Scaled value
4	Map and Text	21	3.1253
5	Map and Voice	18	1.8539
6	Text and Voice	17	1.7274
2	Text	14	1.4478
3	Voice	10	0.9918
1	Map	10	0.0000

Table 30. Results of Thurstone's Scaling Procedure and Newman-Kuels post hoc test results on the Frequency of Preference Data for the Navigational Aids for Female subjects with Low Spatial Ability. (Scaled values with the same letters are not significantly different.)

Condition	Navigational Aid	Frequency of Preference	Scaled value	N-K Test
4	Map and Text	27	7.1159	A
5	Map and Voice	17	4.0672	AB
6	Text and Voice	16	2.9988	B
2	Text	13	1.7025	B
3	Voice	11	1.4994	B
1	Map	6	0.0000	B

Table 31. ANOVA Summary Table for the Subjective Preference Questionnaire Scores for Female participants with Low Spatial Ability.

Source	df	Sum of Squares	Mean Square	F-Value*
Between Navigational Aids	5	185.7108	37.1422	6.1424
Residual	10	60.4684	6.0468	
Total	15	246.1792		

* $p = 0.008$

Table 32. Results of Thurstone's Scaling Procedure and Newman-Kuels post hoc test results on the Frequency of Preference Data for the Navigational Aids for Male subjects with High Spatial Ability. (Scaled values with the same letters are not significantly different.)

Condition	Navigational Aid	Frequency of Preference	Scaled value	N-K Test
4	Map and Text	28	8.2092	A
5	Map and Voice	17	3.1503	B
6	Text and Voice	17	3.1253	B
2	Text	11	1.5244	B
1	Map	11	1.5244	B
3	Voice	6	0.0000	B

Table 33. ANOVA Summary Table for the Subjective Preference Questionnaire Scores for Male participants with High Spatial Ability.

Source	df	Sum of Squares	Mean Square	F-Value*
Between Navigational Aids	5	242.9589	48.5918	7.6632
Residual	10	63.4089	6.3409	
Total	15	306.3678		

* $p = 0.0041$

Table 34. Results of Thurstone's Scaling Procedure on the Frequency of Preference Data for the Navigational Aids for Male subjects with Low Spatial Ability. (Scaled values with the same letters are not significantly different.)

Condition	Navigational Aid	Frequency of Preference	Scaled value
4	Map and Text	26	4.1639
5	Map and Voice	15	2.9223
6	Text	16	2.0570
2	Map	14	1.8290
3	Text and Voice	13	0.7606
1	Voice	6	0.0000

VII. DISCUSSION

Overview

The results of the statistical analyses performed on the experimental data stated in the previous chapter are discussed here. This chapter is organized into sections for each experimental hypothesis. The conclusions drawn from this discussion are presented in the following chapter. Table 35 shows a matrix of the experimental results.

Hypothesis 1

> ***Multiple Resource Theory* - Performance will be better when information is presented using a voice navigational aid.**

This hypothesis predicted that the number of wall hits, the number of navigational errors, and the time to complete task would be less for the voice navigational aid and the voice aid would require less mental effort and would be preferred over other navigational aids.

Navigational aid did not have an effect on the number of wall hits. The expectation for the number of wall hits to be less for the voice navigational aid was not confirmed; there were not fewer wall hits for the voice aid. Since the probability of hitting the walls of the maze would increase as attention to the task of maneuvering decreased, the absence of differences in number of wall hits may be explained by increased attention given for the other navigational aids.

Table 35. Matrix of Experimental Results.

Navigational Aid	Number of Wall Hits	Number of Navigational Errors	Normalized Time to Complete Task	Subjective Workload Question. Scores	Subjective Preference Question. Scores
Map	no diff.	most	no diff.	no diff.	least
Text	no diff.	no diff.	less	highest	less
Voice	no diff.	no diff.	more	no diff.	least
Map & Text	no diff.	no diff.	more	no diff.	most
Map & Voice	no diff.	no diff.	less	no diff.	more
Text & Voice	no diff.	no diff.	less	no diff.	more

The number of navigation errors indicated that the voice navigational aid was significantly better than the map navigational aid. This suggests that, in general, it may be more difficult to extract information from the map than the voice aid. However, there were no significant differences between the voice navigational aid and other navigational aids.

The normalized time to complete task values indicated that it did not take less time to complete the conditions with the voice navigational aid than the other navigational aids. This may be a result of the timing or the length of the messages. When subjects tried to cut across a turn in the maze, they may have been given two instructions at the same time, depending on the situation. This would make it difficult to decide which direction to go. This shows a need for further research in the area of timing and length of messages.

There was no indication from the subjective workload questionnaire scores that the voice navigational aid under either workload condition was better than any other navigational aid, except the text navigational aid under the high workload condition. This may be due to the fact that the voice navigational aid did not require visual attention while the text navigational aid did, and under high workload conditions the subjects felt that the additional visual attention necessary for the text aid required significantly more mental effort.

The expectation that the subjective preference questionnaire scores would show that the voice navigational aid was most preferred was not supported, since it was tied with the map navigational aid for least preferred navigational aid.

In summary, there is no evidence that the multiple resource theory truly explains the navigational behavior shown in the experiment. The analyses of the number of navigation errors and the subjective workload questionnaire scores show that the voice navigational aid was not better than other navigational aids. The number of wall hits did not exhibit support for any single theory. Some support should have been found with the time to complete task analyses and subjective preference questionnaire scores but the results indicate the opposite. Therefore, the observed results do not confirm the multiple resource theory as describing navigational performance and attitudes.

Hypothesis 2

***Stimulus-Central Processing-Response Compatibility Theory* - Performance will be better when information is presented using a map navigational aid.**

This hypothesis predicted that the number of wall hits, the number of navigational errors, and the time to complete task would be less for the map navigational aid and the map aid would require less mental effort and would be preferred over other navigational aids.

Navigational aid did not have an effect on the number of wall hits. The expectation for the number of wall hits to be less for the map navigational aid was not confirmed; there were not fewer wall hits for the map aid.

The anticipation that the number of navigation errors would be less for the map navigational aid than the other navigational aids was not supported; the map navigational aid conditions had significantly higher numbers of navigation errors than the other aids. This may indicate that, in general, it may be more difficult to extract information from the map than the text or voice aid. People may have missed turns or made incorrect turns because they were trying to extract that information from the map. In the dual conditions with the map (map and text aid and map and voice aid), participants may have been attending to the other type of information display, the text or the voice.

The dependent variable normalized time to complete task did not show that the map navigational aid was different than any of the other navigational aids. One reason that there was no difference in the normalized time was that the upcoming turns could be seen ahead of the time and subjects could start processing the information ahead of time. Also, if the subject made an incorrect turn, the mistake could be seen immediately.

The subjective workload questionnaire scores did not indicate that the map navigational aid under either workload condition was better than any other navigational aid, except the text navigational aid under the high workload condition. This may be due to the fact that the map navigational aid allowed the subject to see what to expect while the text navigational aid did not, and under high workload conditions the subjects felt that the inability to anticipate in the text aid resulted in significantly more mental effort.

The expectancy that the subjective preference questionnaire scores would indicate that the map navigational aid was most preferred was not demonstrated. The map aid tied with the voice navigational aid for the least preferred type of navigational aid.

In summary, there is no support for the Stimulus-Central Processing-Response Compatibility Theory. The analyses of the time to complete task and the subjective workload questionnaire scores showed that the map navigational aid was tied with other navigational aids. The number of wall hits did not show support for any single theory. Some support should have been found with the analyses of the number of navigation errors and the subjective preference scores, but the observed results indicate the opposite; the map only navigational aid was found to be the worst (or tied for worst). Therefore, the stimulus-central processing-response compatibility theory was not supported by the empirical results.

Hypothesis 3

> ***Recoding Mechanism Theory* - Performance will be better when information is presented using text or voice navigational aid.**

This hypothesis predicted that the number of wall hits, the number of navigational errors, and the time to complete task would be less for the text or the voice navigational aid and the text or the voice aid would require less mental effort and would be preferred over other navigational aids.

Navigational aid did not have an effect on the number of wall hits. The expectation for the number of wall hits to be less for the text or the voice navigational aid was not confirmed; there were not fewer wall hits for either of these aids.

The number of navigation errors indicated that text navigational aid and the voice navigational aid were significantly better than the map only navigational aid. This may indicate that, in general, it may be more difficult to extract information from the map than the text or voice aid. However, there were no differences between the text or voice aid and any other navigational aid.

The normalized time to complete task values indicated that it did not take less time to complete the conditions with the voice navigational aid than the other navigational aids. However, the text conditions did take significantly less time than the voice aid and the map and text navigational aid conditions. The voice results may be a consequence of the timing or the length of the messages. When subjects tried to cut across a turn in the maze, they may have been given two instructions at the same time, depending on the situation. This would make it difficult to decide which direction to go. The text conditions showed the messages on the screen and may have allowed for wholistic processing of the messages rather than sequential processing like the voice aid required. This would allow the subject to understand the message quickly and not make it necessary for them to wait until the voice message finished.

Analysis of the subjective workload questionnaire scores did not indicate that the text navigational aid under the low workload condition and the voice navigational aid under either workload condition were better than any other navigational aid, except the text navigational aid under the high workload condition. The difference for the voice navigational aids and the text navigational aid under the high workload condition may be due to the fact that the voice navigational aid did not require visual attention while the text navigational aid did, and under high workload conditions the subjects felt that the additional visual attention necessary for the text aid required significantly more mental effort.

The expectancy that the subjective preference questionnaire scores would indicate that the text or the voice navigational aid would be most preferred was not demonstrated. The text navigational aid was more preferred than the map aid and the voice aid, but less than all the other navigational aids.

In summary, there is no significant support for the recoding mechanism theory. The analysis of the number of wall hits did not show support for any single theory. The number of navigation errors, the time to complete task, and the subjective workload questionnaire scores showed that the text navigational aid and the voice navigational aid tied with other aids. Some support should have been found with the subjective preference questionnaire scores but there was none. Therefore, the observed results do not confirm the recoding mechanism theory.

Hypothesis 4

> ***Dual Coding Theory* - Performance will be better when information is presented using a text or voice navigational aid and a map navigational aid at the same time.**

This hypothesis predicted that the number of wall hits, the number of navigational errors, and the time to complete task would be less for the map and text or the map and voice navigational aid and the map and text or the map and voice aid would require less mental effort and would be preferred over other navigational aids.

Navigational aid did not have an effect on the number of wall hits. The expectation for the number of wall hits to be less for the map and text or the map and voice was not supported; there were not fewer wall hits with these aids than with any other.

The number of navigation errors indicated that map and text navigational aid and the map and voice navigational aid were significantly better than the map navigational aid. This may indicate that in the dual conditions with the map (map and text aid and map and voice aid), participants may have been attending to the other type of information display, the text or the voice.

The normalized time to complete task values indicated that it did not take less time to complete the conditions with the map and text navigational aid than the other navigational aids, while the map and voice conditions did take significantly less time than the voice aid and the map and text navigational aid conditions. The map and text navigational aid may have taken longer to use since all the information was visual. The subjects were required to perform a visual task while obtaining information from two different visual displays. For the map and voice navigational aid, subjects could see what was coming up in the map and get the correct timing of required turns from the voice message.

There was no indication from the subjective workload questionnaire scores that that the map and text navigational aid or the map and voice navigational aid under either workload condition were better than all other navigational aids except the text navigational aid under the high workload condition. This may be due to the fact that both the map and text navigational aid and the map and voice navigational aid allowed the subject to see what to expect while the text navigational aid did not, and under high workload conditions the subjects felt that the inability to anticipate in the text aid resulted in significantly more mental effort.

The subjective preference questionnaire scores indicated that the map and text navigational aid was the most preferred type of navigational aid. The map and voice navigational aid and the text and voice navigational aid were rated second. All the dual conditions (map and text, map and voice, and text and voice) were rated higher than the single conditions (map, text, and voice).

In summary, there is support for the dual coding theory, but not to the level supposed by the hypothesis. The number of navigation errors analysis and the subjective workload questionnaire scores analysis showed that the map and text aid and the map and voice aid tied with other navigational aids. Analysis of the normalized time to complete task indicated that the map and voice navigational aid took less time than some of the other navigational aids. Analysis of the subjective preference questionnaire scores showed that the map and text navigational aid was the most preferred. The other dual conditions were rated second indicating that the presentation of information in more than one way is a good idea. Therefore, the empirical results support the dual coding theory.

Hypothesis 5

Spatial Ability ***-***

- ***high SA subjects perform better with spatial navigational aids than low SA subjects***
- ***high SA subjects will rate spatial navigational aids as less workload intensive than low SA subjects***

- ***high SA subjects will prefer spatial navigational aids more than low SA subjects will***

The significant increase in the number of wall hits for low spatial ability subjects may be due to low spatial ability subjects having a more difficult time switching back and forth between displays (the navigational aid and the maze environment). Another explanation for the differences may be due to a greater processing time or greater amount of attention required by low spatial ability subjects to understand what the necessary response should be.

There were significantly more navigational errors made by subjects with low spatial ability than those with high spatial ability. The analysis shows that subjects with low spatial ability made significantly more navigational errors when using the map navigational aid. This supports the hypothesis that people with higher spatial ability will perform better with spatial navigational aids than those with lower spatial ability.

There were no trends shown for the dependent variable time to complete task.

There was no effect of spatial ability on the subjective workload questionnaire scores. This indicates that high and low spatial ability subjects did not rate the spatial navigational aids significantly differently.

Low spatial ability subjects rated the map and text navigational aid as the most preferred aid, while the map and the voice navigational aids were rated as the least preferred. Low spatial ability subjects rated the text, the map and voice, and the text and voice navigational as falling in the middle. High spatial ability subjects rated the map and text navigational aid as significantly better than the map, text, voice, and map and voice navigational aids; the text and voice navigational aid was not rated significantly differently than any other aid.

The observed results indicate that spatial ability has an effect on the number of navigation errors when using spatial navigational aids, such as the map. The number of wall hits was influenced by spatial ability but there was no indication that the use of spatial navigational aids (map aid) resulted in poorer performance than the use of verbal aids (text and voice aids). There was no support for differences in spatial ability shown by the analyses of time to complete task or subjective workload questionnaire scores. The map and text navigational aid was the most preferred by all subjects. The observed results show support for the hypothesis that individual differences in spatial ability has a significant effect on navigational performance and no support for the hypothesis that spatial ability has an effect on the subjective opinion of workload or preference.

Other Results

Gender was not included in any of the hypotheses, but some differences were found during the analyses. Gender was found to be significant for the dependent variable time to complete task. Females took longer to complete the conditions than males. Males preferred the map and text navigational aid significantly more than all other navigational aids. Females preferred the map and text navigational aid significantly more than all other navigational aids, except the text and voice navigational aid which was not found to be preferred significantly differently than any other navigational aid.

Analysis of the subjective workload questionnaire scores indicated a significant main effect of Workload level. This indicates that the low ("smooth" condition) and high (perturbations in position) workload conditions for the navigational aids were different enough to allow testing of the cognitive theories. The effect of the Navigational Aid main effect was weak in the analysis of the subjective workload questionnaire scores; the Newman-Keuls post hoc test showed no significant differences. Considering the strong Workload main effect and the Workload x Navigational Aid interaction and the vague results of the subsequent analysis of the Navigational Aid main effect limits the conclusions that can be drawn from it.

VIII. CONCLUSIONS, DESIGN RECOMMENDATIONS, AND FUTURE WORK

Conclusions

This study provides additional evidence that knowledge of the entire driving task (vehicle, driver, and environment) is necessary when designing or adding a navigational display into a vehicle. If the driving task at hand requires a great deal of attention (high workload situation), map only or text only navigational aids may not be easy to use or process information from. Voice only navigational aids may introduce problems when used by people with a wide variety of hearing levels or in situations where the environmental noise prohibits the detection of navigational information. Using redundant messages, such as in the dual presentation scenarios, may be a solution. Allowing the users to change levels or choose which type of display to use is another option. But a danger in allowing this is the possibility of the driver not selecting the optimal type of display for the driving task at hand.

This research was done to gather information about the presentation of navigational information. The cognitive theory for the presentation of navigational information best supported is the dual coding theory. People prefer to have redundant navigational information available, whether it is verbal and spatial (map and text or map and voice aids) or both verbal (text and voice aids), rather than a single type of information, such as the map only, text only, or voice only navigational aids.

Spatial ability had an effect on the performance measures of number of wall hits and number of navigational errors. It was not significant on time to complete task or subjective workload questionnaire scores. One of the problems with attempting to assess some part of human performance or human behavior using any kind of subjective scale, such as the Modified Cooper-Harper Scale, is the fact that people do not like to rate a task as being particularly difficult or requiring a significant amount of mental effort. People feel that it reflects on themselves as having a problem, not the system, even though directions are explicitly given about problems being system related not person related.

Design Recommendations

The empirical results indicate that the map navigational aid is not effective under high workload conditions or by people with low spatial ability. This indicates that map navigational aids by themselves are not the way to go, but that is what is being produced right now. Since dual navigational aids (information presented in two ways simultaneously) seem to take less time to use and are preferred over single navigational aids (information is presented in one way only), designers should present redundant navigational information. The voice and map navigational aid resulted in the greatest level of performance and were more preferred.

Future Work

Due to the Intramodal Transportation Efficiency Act of 1991 and other similar legislation, in addition to the growing interest in making "smart" roads a reality, there is a concern for the possibility of overloading the driver with too much information presented in ways that are difficult to process. Some areas that need to be researched further are timing of messages, length of messages, and the differences in information needed in familiar versus unfamiliar environments. This study used a virtual reality package so changes could be made fairly rapidly and easily. More research should be done on using desktop virtual reality systems for testing a wide variety of environments. Additional driving research needs to be done in both driving simulators and "on the road" to assess how the presentation of information effect the actual driving task.

The design of navigational devices must be guided by human factors considerations to reduce unsafe operations. Although an on-board unit may aid drivers in a given task, its operation may also introduce significant hazards.

IX. REFERENCES

Akamatsu, M., Yoshioka, M., Imacho, N., and Kawashima, H. (1994). Driving with a car navigation system - Analysis of landmarks by the thinking aloud method. *Proceedings of the 12th Triennial Congress of the International Ergonomics Association, Toronto, Canada, 15-19 August 1994*, 148-150.

Antin, J.F. (1987). *Automobile Navigation Methods: Effectiveness, Efficiency, and Strategy*, Unpublished doctoral dissertation, Virginia Polytechnic Institute and State University, Blacksburg, VA.

Antin, J.F. (1993). Informational aspects of car design: Navigation. In *Automotive Ergonomics*, Ed. by B. Peacock and W. Karwowski, London: Taylor and Francis.

Antin, J.F., Dingus, T.A., Hulse, M.C., and Wierwille, W.W. (19868). Human factors test and evaluation of an automobile moving-map navigation system, Part I: Attentional demand requirements; Part II: Methodology issues - Effectiveness, efficiency, and strategy. Blacksburg, VA: Virginia Polytechnic Institute and State University.

Antin, J.F., Dingus, T.A., Hulse, M.C., and Wierwille, W.W. (1988). The effects of spatial ability on automobile navigation. *Trends in Ergonomics/Human Factors V*, Ed. by F. Aghazadeh, NY: Elsevier Science Publishers, B.V.

Antin, J.F., Dingus, T.A., Hulse, M.C., and Wierwille, W.W. (1990). An evaluation of the effectiveness and efficiency of an automobile moving-map navigational display. *International Journal of Man-Machine Studies*, 33, 301-315.

Aretz, A.J. (1989). Spatial cognition and navigation. In *Proceedings of the Human Factors Society, 33rd Annual Meeting, Denver, CO, 16-20 October 1989,* Santa Monica, CA: Human Factors Society.

Aretz, A.J. (1990). Map display design. In *Proceedings of the Human Factors Society, 34th Annual Meeting, Orlando, FL, 8-12 October 1990,* Santa Monica, CA: Human Factors Society.

Avolio, B.J., Kroeck, K.G., and Panek, P.E. (1985). Individual differences in information-processing ability as a predictor of motor vehicle accidents. *Human Factors*, 27, 577-587.

Baddeley, A.D. (1986). *Working Memory*, Oxford: Clarendon.

Barb, K.H. and Mast, T. (1992). *Intelligent Vehicle Highway Systems (IVHS) Safety and Human Factors Considerations, IVHS-AMER-ATMS-92-1*, Washington D.C.: IVHS America.

Bartlett, J.C., Till, R.E., and Levy, J.C. (1980). Retrieval characteristics of complex pictures: Effect of verbal encoding. *Journal of Verbal Learning and Verbal Behavior*, 19, 430-449.

Bartram, D.J. (1980). Comprehending spatial information: The relative efficiency of different methods of presenting information about bus routes. *Journal of Applied Psychology*, 65(1), 103-110.

Bonsall, P.W. and Parry T. (1990). Drivers' requirements for route guidance. *Third International Conference on Road Traffic Control*, 1-5.

Brandimonte, M.A. and Gerbino, W. (1993). Mental image reversal and verbal recoding: When ducks become rabbits. *Memory and Cognition*, 21(1), 23-33.

Brandimonte, M.A., Hitch, G.J., and Bishop, D.V.M. (1992). Verbal recoding of visual stimuli impairs mental image transformations. *Memory and Cognition*, 20(4), 449-455.

Burgett, A.L. (1991). Safety evaluation of TravTek. In *Vehicle Navigation and Information Systems Conference Proceedings*, Volume 2, Warrendale, PA: SAE.

Burnett, G.E., and Joyner, S.M. (1994). An assessment of route guidance systems and their implications for driver safety. *Proceedings of the 12th Triennial Congress of the International Ergonomics Association, Toronto, Canada, 15-19 August 1994*, 156-158.

Byrne, R.W. (1979). Memory for urban geography. *Quarterly Journal of Experimental Psychology*, 31, 147-154.

Card, S.K., Moran, T.P., and Newell, A. (1983). *The Psychology of Human-Computer Interaction*, Hillsdale, NJ: Lawrence Erlbaum Associates.

Carter, R. and Woldstad, J. (1985). Repeated measurements of spatial ability with the manikin test. *Human Factors*, 27(2), 209-219.

Casali, J.G. (1982). *A Sensitivity/Intrusion Comparison of Mental Workload Estimation Techniques Using a Simulated Flight Task Emphasizing Perceptual Piloting Behaviors*, Unpublished doctoral dissertation, Virginia Polytechnic Institute and State University, Blacksburg, VA.

Catling, I., Harris, R., and McQueen, B. (1991). A review of European developments in route guidance and navigation systems. In *Applications of Advanced Technologies in Transportation Engineering, Proceedings of the 2nd International Conference, Minneapolis, MN, 18-21 Aug. 1991*, Ed.

by Y.J. Stephanedes and K.C. Sinha, NY: American Society of Civil Engineering.

Catling, I. and McQueen, B. (1990). Road transport informatics in Europe - a summary of current developments. In *Proceedings of the 5th Jerusalem Conference on Information Technology, Jerusalem, Israel, 22-25 Oct. 1990*, Los Alamitos, CA: IEEE Computer Society Press.

Chen, H., Ho., C., and Lee, C. (1991). Recent progress for intelligent vehicle/highway system development in Taiwan. In *Vehicle Navigation and Information Systems Conference Proceedings*, Volume 2, Warrendale, PA: SAE.

Chen, K. and Galler, B.A. (1990). An overview of intelligent vehicle-highway systems (IVHS) activities in North America. In *Proceedings of the 5th Jerusalem Conference on Information Technology, Jerusalem, Israel, 22-25 Oct. 1990*, Los Alamitos, CA: IEEE Computer Society Press.

Corsini, R.J. (1987). *Concise Encyclopedia of Psychology*, NY: John Wiley and Sons.

Cyganiak, N. (1987). Auto maps computer map design. *The American Cartographer*, 14(3), July, 269-274.

Daniel, T.C. and Ellis, H.C. (1972). Stimulus codability and long-term recognition memory for visual form. *Journal of Experimental Psychology*, 93, 83-89.

Dewar, R.E. (1988). In-vehicle information and driver overload. *International Journal of Vehicle Design*, vol. 9, nos. 4/5, 557-564.

Dingus, T.A. (1987). *Attentional Demand Evaluation for an Automobile Moving-Map Navigation System*, Unpublished doctoral dissertation, Virginia Polytechnic Institute and State University, Blacksburg, VA.

Dingus, T.A., Antin, J.F., Hulse, M.C., and Wierwille, W.W. (1988). Human factors associated with in-car navigation system usage. In *Proceedings of the Human Factors Society 32nd Annual Meeting, New York City, NY, 19-22 Oct. 1988*, Santa Monica, CA: Human Factors Society.

Dingus, T.A., Antin, J.F., Hulse, M.C., and Wierwille, W.W. (1989). Attentional demand requirements of an automobile moving-map navigation system. *Transportation Research-A*, 23A(4), 301-315.

Dingus, T.A. and Hulse, M.C. (1993). Human factors research recommendations for the development of design guidelines for advanced traveler information systems. In *Proceedings of the Human Factors and Ergonomics Society 37th Annual Meeting, Seattle, WA, 11-15 Oct. 1993*, Santa Monica, CA: Human Factors and Ergonomics Society.

Dingus, T.A., Hulse, M.C., Krage, M.K., Szczublewski, F.E., and Berry, P. (1991). A usability evaluation of navigation and information system "pre-drive" functions. *SAE Technical Paper Series, 912794*, Warrendale, PA: SAE.

Eberts, R.E. and Posey J.W. (1990). The mental model in stimulus-response compatibility. In *Stimulus-Response Compatibility*, Ed. by R.W. Proctor and T.G. Reeve, NY: Elsevier Science Publishers, B.V.

Eggemeier, F.T. and O'Donnell, R.D. (1982). A conceptual framework for development of a workload assessment methodology. In *Text of the*

Remarks Made at the 1982 American Psychological Association Annual Meeting, Washington, DC: American Psychological Association.

Ekstrom, R.B., French, J.W., and Harman, H.H. (1976). *Manual for Kit of Factor-Referenced Cognitive Tests*, Princeton, NJ: Educational Testing Services.

Ellis, H.C. and Daniel, T.C. (!971). Verbal processes in long-term recognition memory. *Journal of Experimental Psychology*, 90, 18-26.

Fairclough, S. and Maternaghan, M. (1993). Changes in drivers' visual behaviour due to the introduction of complex versus simple route navigation information. In *Visual Search 2*, Ed. by D. Brogan, A. Gale, and K. Carr, London: Taylor and Francis.

Fitts, P.M. and Seeger C.M. (1953). S-R compatibility: Spatial characteristics of stimulus and response codes. *Journal of Experimental Psychology*, 46(3) September, 199-210.

Fleischman, R.N. (1991). Research and evaluation plans for the TravTek IVHS operational field test. In *Vehicle Navigation and Information Systems Conference Proceedings*, Volume 2, Warrendale, PA: SAE.

Fleischman, R.N., Carpenter, J.T., Dingus, T.A., Szczublewski, F.E., Krage, M.K., and Means, L.G. (1991). Human factors in the TravTek demonstration project: Getting information to the driver. In *Proceedings of the Human Factors Society , 35th Annual Meeting, San Francisco, CA, 2-6 September 1991* Santa Monica, CA: Human Factors Society.

Fowkes, M. (1984). Presenting information to the driver. *Displays: Technology and Applications*, 5(4), Oct., 215-223.

Gescheider, G.A. (1985). *Psychophysics: Method, Theory, and Application*, Hillsdale, NJ: Lawrence Erlbaum Associates.

Green, P. (1992). *American Human Factors Research on In-Vehicle Navigation Systems*, Technical Report UMTRI-92-47, December.

Green, P., Serafin, C., Williams, M., and Paelke, G. (1991). What functions and features should be in driver information systems of the year 2000. In *Vehicle Navigation and Information Systems Conference Proceedings*, Warrendale, PA: SAE.

Guilford, J.P. (1954). *Psychometric Methods*, NY: McGraw-Hill.

Hancock, P.A. (1988). The effect of gender and time of day upon the subjective estimate of mental workload during the performance of a simple task. In *Human Mental Workload*, Ed. by P.A. Hancock and N. Meshkati, NY: Elsevier Science Publishers, B.V.

Hancock, P.A. (1989). The effect of performance failure and task demand on the perception of mental workload. *Applied Ergonomics*, 20, 197-205.

Hancock, P.A. and Parasuraman, R. (1992). Human factors and safety in the design of intelligent vehicle-highway systems (IVHS). *Journal of Safety Research*, vol. 23, 181-198.

Hancock, P.A., Rodenberg, G.J., Mathews, W., and Vercruyssen, M. (1988). Estimation of duration and mental workload at differing times of the day by males and females. In *Proceedings of the Human Factors Society 32nd Annual Meeting, New York City, NY, 19-22 Oct. 1988*, Santa Monica, CA: Human Factors Society.

Hicks, T.G. and Wierwille, W.W. (1979). Comparison of five mental workload assessment procedures in a moving-base driving simulator. *Human Factors*, 21(2), 129-143.

IVHS America (1992). *Intelligent Vehicle Highway Systems (IVHS) Safety and Human Factors Considerations, IVHS-AMER-ATMS-92-1.*

Jacobson, R. (1994). Virtual worlds capture spatial reality. *GIS World*, December, 36-39.

Jeffery, D.J., Russam, K., and Robertson, D.I. (1989). Electronic route guidance by AUTOGUIDE: The research background. *Traffic Engineering and Control*, 28, 525-529.

Johns, R.C. (1991). Academic research efforts in the GuideStar IVHS program. In *Applications of Advanced Technologies in Transportation Engineering, Proceedings of the 2nd International Conference, Minneapolis, MN, 18-21 Aug. 1991*, Ed. by Y.J. Stephanedes and K.C. Sinha, NY: American Society of Civil Engineering.

Jovanis, P.P. and Kitamura, R. (1989). User perceptions and safety implications of in-vehicle navigation systems. *IEEE*, 6, 113-116.

Kantowitz, B.H. and Casper, P.A. (1988). Human workload in aviation. In *Human Factors in Aviation*, Ed. by E.L. Wiener and D.C. Nagel, San Diego, CA: Academic Press.

Katakura, M. and Saito, M. (1991). Assessment of IVHS research efforts in Japan and future directions. In *Applications of Advanced Technologies in Transportation Engineering, Proceedings of the 2nd International Conference, Minneapolis, MN, 18-21 Aug. 1991*, Ed. by Y.J. Stephanedes and K.C. Sinha, NY: American Society of Civil Engineering.

Kimura, K., Maranuaka, K., and Sugiura, S. (1994). Human factors considerations for automotive navigation systems. *Proceedings of the*

12th Triennial Congress of the International Ergonomics Association, Toronto, Canada, 15-19 August 1994, 162-165.

Kirwan, B. and Ainsworth, L.K. (1993). *A Guide to Task Analysis*, Washington, DC: Taylor and Francis.

Kishi, H., Asami, T., Ishikawa, S. and Itoh, T. (1990). Development of a standalone navigation and audio-visual system (Multi-AV system). *Automotive Electronic Displays and Information Systems, SP-809*, Warrendale, PA: SAE.

Kishi, H. and Sugiura, S. (1993). Human factors considerations for voice route guidance. *SAE Technical Paper Series, 930553*, Warrendale, PA: SAE.

Kosslyn, S.M. (1980). *Image and the Mind*, Cambridge: Harvard University Press.

Kramer, U. and Rohr, G. (1982). A model of driver behaviour. *Ergonomics*, 25(10), 891-907.

Kuipers, B. (1983). Modeling human knowledge of routes: Partial knowledge and individual variation. *Proceedings of the AAAI 1983 Conference*, Menlo Park, CA: The American Association of Artificial Intelligence.

Labiale, G. (1989). Influence of in car navigation map displays on drivers performances. *SAE Technical Paper 891683*, Warrendale, PA: SAE.

Labiale, G. (1990). In-car road information: Comparisons of auditory and visual representations. In *Proceedings of the Human Factors Society, 34th Annual Meeting, Orlando, FL, 8-12 October 1990*, Santa Monica, CA: Human Factors Society.

Lee, J.D., Morgan, J., Raby, M., and Wheeler, W.A. (1994). Accommodating driver needs and limits: A functional description of ATIS/CVO systems.

Proceedings of the 12th Triennial Congress of the International Ergonomics Association, Toronto, Canada, 15-19 August 1994, 140-142.

Lindal, J. (1994). *Mazer 3-D software, v3.0.*

Lohman, D.F. (1979). *Spatial Ability: A Review and Reanalysis of the correlational literature* (Tech. Rep. No. 8), Stanford, CA: Aptitude Research Project, School of Education, Stanford University.

Lund, S.A. (1990). Intelligent vehicle/highway systems in the U.S. - In need of a vision. *SAE Technical Paper Series, 910871*, Warrendale, PA: SAE.

Lunenfeld, H. (1989). Human factor considerations of motorist navigation and information systems. In *Vehicle Navigation and Information Systems Conference Proceedings*, Warrendale, PA: SAE.

Maccoby, E.E. and Jacklin, C.N. (1974). *The Psychology of Sex Differences*, Stanford, CA: Stanford University Press.

Mark, D.M. and McGranaghan, M. (1986). Effective provision of navigation assistance to drivers: A cognitive science approach. *Proceedings of Auto Carto London, 14-19 September 1986*, London: International Cartographic Association.

Mast, T. (1991). Human factors in intelligent vehicle-highway systems: A look to the future. In *Proceedings of the Human Factors Society, 35th Annual Meeting, San Francisco, CA, 2-6 September 1991*, Santa Monica, CA: Human Factors Society.

McCauley, M.E., Clarke, D.L., Sharkey, T.J., and Dingus, T.A. (1994). Comparable systems analysis of advanced traveler information systems. *Proceedings of the 12th Triennial Congress of the International Ergonomics Association, Toronto, Canada, 15-19 August 1994*, 143-145.

McGranaghan, M., Mark, D.M., and Gould, M.D. (1987). Automated provision of navigation assistance to drivers. *The American Cartographer*, 14(2), 121-138.

McQueen, B. and Catling, I. (1991). The development of IVHS in Europe. *IVHS and Vehicle Communications*, SP-877, August 1991, Warrendale, PA: Society of Automotive Engineers, Inc.

Meyers, L.S. and Rhoades, R.W. (1978). Visual search of common scenes. *Quarterly Journal of Experimental Psychology*, 30, 297-310.

Mollenhauer, M.A., Lee, J., Cho, K., Hulse, M.C. and Dingus, T.A. (1994). The effects of sensory modality and information priority on in-vehicle signing and information systems. In *Proceedings of the Human Factors and Ergonomics Society, 38th Annual Meeting, Nashville, TN, 24-28 October 1994*, Santa Monica, CA: Human Factors and Ergonomics Society.

Neale, D.C. (1995). *Spatial Perception in Perspective Displays as a Function of Field-of-View and Virtual Environment Enhancements Based on Visual Momentum Techniques*, Unpublished master's thesis, Virginia Polytechnic Institute and State University, Blacksburg, VA.

Noy, Y.I. (1989). Intelligent route guidance: Will the new horse be as good as the old. Canadian Copyright, 49-55.

Noy, Y.I. (1990). Selective attention with auxiliary automobile displays. In *Proceedings of the Human Factors Society 34th Annual Meeting, Orlando, FL, 8-12 October 1990*, Santa Monica, CA: Human Factors Society.

Owens, D.A., Helmers, G., and Sivak, M. (1993). Intelligent vehicle highway systems: A call for user centered design. *Ergonomics*, 36(4) 363-369.

Paivio, A. (1986). *Mental Representations: A Dual Coding Approach*, NY: Oxford University Press.

Paivio, A. (1989). A dual coding perspective on imagery and the brain. In *Neuropsychology of Visual Perception*, Ed. by J.W. Brown, Hillsdale, NJ: Lawrence Erlbaum Associates.

Paivio, A. (1991). Dual coding theory: Retrospect and current status. *Canadian Journal of Psychology*, 45(3), 255-287.

Parkes, A.M., Ashby, M.C., and Fairclough, S.H. (1991). The effects of different in-vehicle route information displays on driver behaviour. In *Vehicle Navigation and Information Systems Conference Proceedings*, Volume 1, Warrendale, PA: SAE.

Parkes, A.M. and Coleman, N. (1990). Route guidance systems: A comparison of methods of presenting directional information to the driver. *Contemporary Ergonomics 1990*, Ed. by E.J. Lovesey, London: Taylor and Francis.

Perez, W.A. and Mast, T.M. (1992). Human factors and advanced traveler information systems (ATIS). In *Proceedings of the Human Factors Society, 36th Annual Meeting, Atlanta, GA, 12-16 October 1992*, Santa Monica, CA: Human Factors Society.

Petchenik, B.B. (1989). The nature of navigation: Some difficult cognitive issues in automatic vehicle navigation. In *Vehicle Navigation and Information Systems Conference Proceedings*, Warrendale, PA: SAE.

Polson, M.C. and Friedman, A. (1988). Task-sharing within and between hemispheres: A multiple-resources approach. *Human Factors*, 30, 633-643.

Popp, M.M. and Farber, B. (1991). Advanced display technologies, route guidance systems, and the position of displays in cars. In *Vision in Vehicles—III*, Ed. by A.G. Gale, et al., NY: Elsevier Science Publishers, B.V.

Posner, M.I. (1969). Abstraction and the process of recognition. In *The Psychology of Learning and Motivation*, Volume 3, Ed. by G.H. Bower and J.T. Spence, New York: Academic Press.

Posner, M.I., Boies, S.J., Eichelman, W.H., and Taylor, R.L. (1969). Retention of visual and name codes of single letters. *Journal of Experimental Psychology Monographs*, 79, 1-16.

Ram, B. and Al-Awadhi, W. (1989). An efficient navigational aid for road travel. *Proceedings of the 11th Annual Conference on Computers and Industrial Engineering*, 17(1-4), 561-564.

Rillings, J.H. and Betsold, R.J. (1990). An advanced driver information system for North America. *Vehicle Electronics in the 90's: Proceedings of the International Congress on Transportation Electronics*, Warrendale, PA: SAE.

Rockwell, T. (1972). Skills, judgment and information acquisition in driving. In *Human Factors in Highway Safety Research*, Ed. by T.W. Forbes, NY: Wiley-Interscience.

Ross, T., Vaughan, G., and Nicolle, C. (1994). Developing human factors design guidelines for route guidance and navigation systems. *Proceedings of the 12th Triennial Congress of the International Ergonomics Association, Toronto, Canada, 15-19 August 1994.*

Russell Shields, T. (1991). The future of vehicle navigation systems. *International Journal of Vehicle Design*, 12(1), 1-7.

Sanders, M.S. and McCormick, E.J. (1993). *Human Factors in Engineering and Design*, NY: McGraw-Hill.

Schlegel, R.E. (1993). Driver mental workload. In *Automotive Ergonomics*, Ed. by B. Peacock and W. Karwowski, London: Taylor and Francis.

Schmandt, C.M. and Davis, J.R. (1989). Synthetic speech for real time direction giving. *IEEE Transactions on Consumer Electronics*, 649-653.

Shekhar, S., Coyle, M.S., Shargal, M., Kozak, J.J., and Hancock, P.A. (1991). Design and validation of headup displays for navigation in IVHS. In *Vehicle Navigation and Information Systems Conference Proceedings*, Volume 1, Warrendale, PA: SAE.

Shields, T.R. (1991). The future of vehicle navigation systems. *International Journal of Vehicle Design*, 12(1), 1-7.

Simon, J.R. (1990) The effects of an irrelevant directional cue on human information processing. In *Stimulus-Response Compatibility*, Ed. by R.W. Proctor and T.G. Reeve, NY: Elsevier Science Publishers, B.V.

Siuru, B. (1990). Heading down the intelligent highway. *Mechanical Engineering*, October, 72-75.

Srinivasan, R., Jovanis, P., Yang, C., and Kitamura, R. (1994). Simulation tests of driving performance with selected route guidance devices. *Proceedings of the 12th Triennial Congress of the International Ergonomics Association, Toronto, Canada, 15-19 August 1994*, 151-155.

Stasz, C. and Thorndyke, P.W. (1980). *The Influence of Visual-Spatial Ability and Study Procedures on Map Learning Skill, N-1501-ONR*, June, Office of Naval Research.

Streeter, L.A. and Vitello, D. (1986). A profile of drivers' map-reading abilities. *Human Factors*, 28(2), 223-239.

Streeter, L.A., Vitello, D., and Wonsiewicz, S.A. (1985). How to tell people where to go: Comparing navigational aids. *International Journal of Man-Machine Studies*, 22, 549-562.

Suchowerskyj, W.E. (1990). Vehicle navigation and information systems in Europe - An overview. *Vehicle Electronics in the 90's: Proceedings of the International Congress on Transportation Electronics*, Warrendale, PA: SAE.

Thorndyke, P.W. and Hayes-Roth, B. (1982). Differences in spatial knowledge acquired from maps and navigation. *Cognitive Psychology*, 14, 560-589.

Thorndyke, P.W. and Stasz, C. (1980). Individual differences in procedures for knowledge acquisition from maps. *Cognitive Psychology*, 12, 137-175.

Thurstone, L.L. (1927). A law of comparative judgment. *Psychological Review*, 34, 273-286.

Torgerson, W.S. (1958). *Theory and Methods of Scaling*, NY: Wiley.

Transportation Research Board (1993). *Primer on Intelligent Vehicle Highway Systems, Transportation Research Circular 412, August 1993*, Washington, D.C.: Transportation Research Board.

Umiltá, C. and Nicoletti, R. (1990). Spatial stimulus-response compatibility. In *Stimulus-Response Compatibility*, Ed. by R.W. Proctor and T.G. Reeve, NY: Elsevier Science Publishers, B.V.

Verwey, W.B. (1989). Simple in-car route guidance information from another perspective: Modality versus coding. *IEEE*, 6, 56-60.

Verwey, W.B. (1990). *Adaptable Driver-Car Interfacing and Mental Workload: A Review of the Literature*, TNO Report IZF 1990 B-3.

Verwey, W.B., Alm, H., Groeger, J.A., Janssen, W.H., Kuiken, M.J., Schraagen, J.M., Schumann, J., van Winsum, W., and Wontorra, H. (1993). GIDS functions. In *Generic Intelligent Driver Support*, Ed. by J.A. Michon, London: Taylor and Francis.

Vicente, K.J. (1987). *Accommodating Individual Differences in Searching a Hierarchical File System*, Unpublished master's thesis, Virginia Polytechnic Institute and State University, Blacksburg, VA.

Walker, J., Alicandri, E., Sedney, C., and Roberts, K. (1991). In-vehicle navigation devices: Effects on the safety of driver performance. In *Vehicle Navigation and Information Systems Conference Proceedings*, Volume 1, Warrendale, PA: SAE.

Wetherell, A. (1981). The efficacy of some auditory-vocal subsidiary tasks as measure of the mental load on male and female drivers. *Ergonomics*, 24, 197-214.

Wheeler, W.A., Lee, J.D., Raby, M., Kinghorn, R.A., Bittner, A.C. Jr., and McCallum, M.C. (1994). Predicting driver behavior using advanced traveler information systems. In *Proceedings of the Human Factors and Ergonomics Society, 38th Annual Meeting, Nashville, TN, 24-28 October 1994*, Santa Monica, CA: Human Factors and Ergonomics Society.

Wickens, C.D. (1980). The structure of attentional resources. In *Attention and Performance VIII*, Ed. by R.S. Nickerson, Hillsdale, NJ: Lawrence Erlbaum Associates.

Wickens, C.D. (1984). Processing resources in attentional. In *Varieties of Attention*, Ed. by R. Parasuraman and D.R. Davies, London: Academic Press.

Wickens, C.D. (1992). *Engineering Psychology and Human Performance*, New York, NY: HarperCollins.

Wickens, C.D., Sandry, D., and Vidulich, M. (1983). Compatibility and resource competition between modalities of input, central processing, and output. *Human Factors*, 25(2), 227-248.

Wickens, C.D., Vidulich, M., and Sandry-Garza, D., (1984). Principles of S-C-R compatibility with spatial and verbal tasks: The role of display-control location and voice-interactive display control interfacing. *Human Factors*, 26(5), 533-543.

Wierwille, W.W., Casali, J.G., Connor, S.A., and Rahimi, M. (1985). Evaluation of the sensitivity and intrusion of mental workload estimation techniques. In *Advances in Man-Machine Systems Research, Volume 2*, Ed. by W.B. Rouse, Greenwich, CN: JAI Press Inc.

Wierwille, W.W., Hulse, M.C., Fischer, T.J., and Dingus, T.A. (1988). Strategic use of visual resources by the driver while navigating with an in-car navigation display system. *SAE P-211, 885180*, Warrendale, PA: SAE.

Wierwille, W.W., Hulse, M.C., Fischer, T.J., and Dingus, T.A. (1991). Visual adaptation of the driver to high-demand driving situations while navigating with an in-car navigation system. In *Vision in Vehicles—III*, Ed. by A.G. Gale, et al., NY: Elsevier Science Publishers, B.V.

Williges, R.C. (1993). *ISE 5615: Human Factors Research Design I*, class notes, Fall Semester.

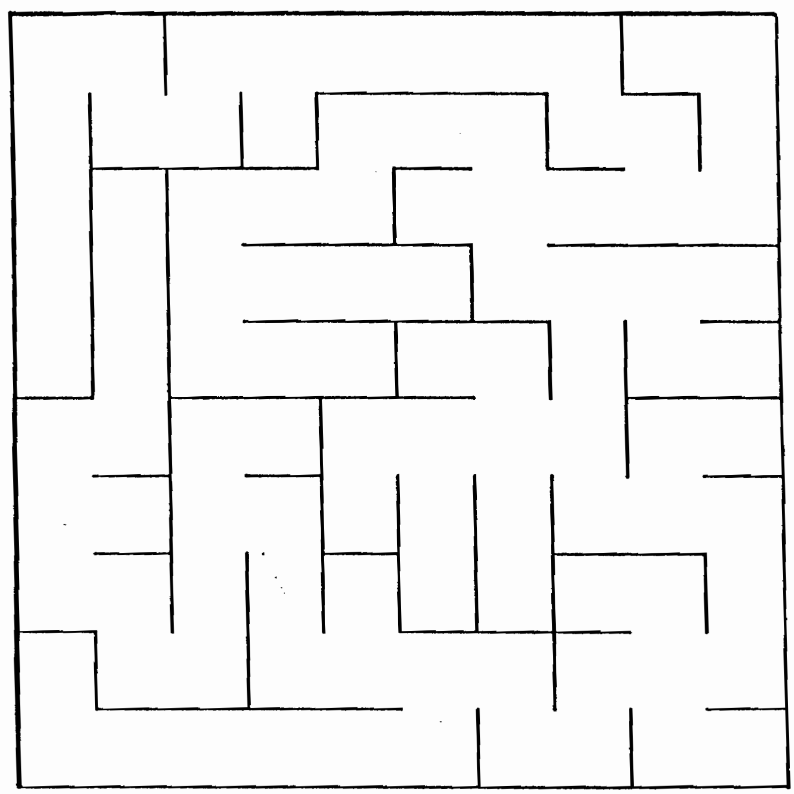
Winer, B.J., Brown, D.R., and Michels, K.M. (1991). *Statistical Principles in Experimental Design*, NY: McGraw-Hill.

APPENDICES

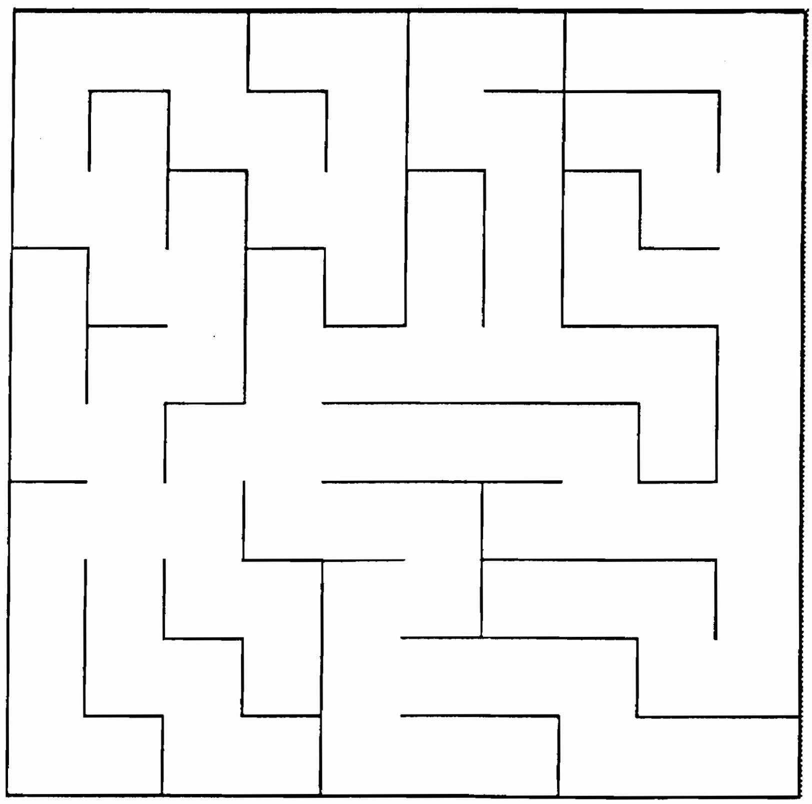
APPENDIX A

Mazes

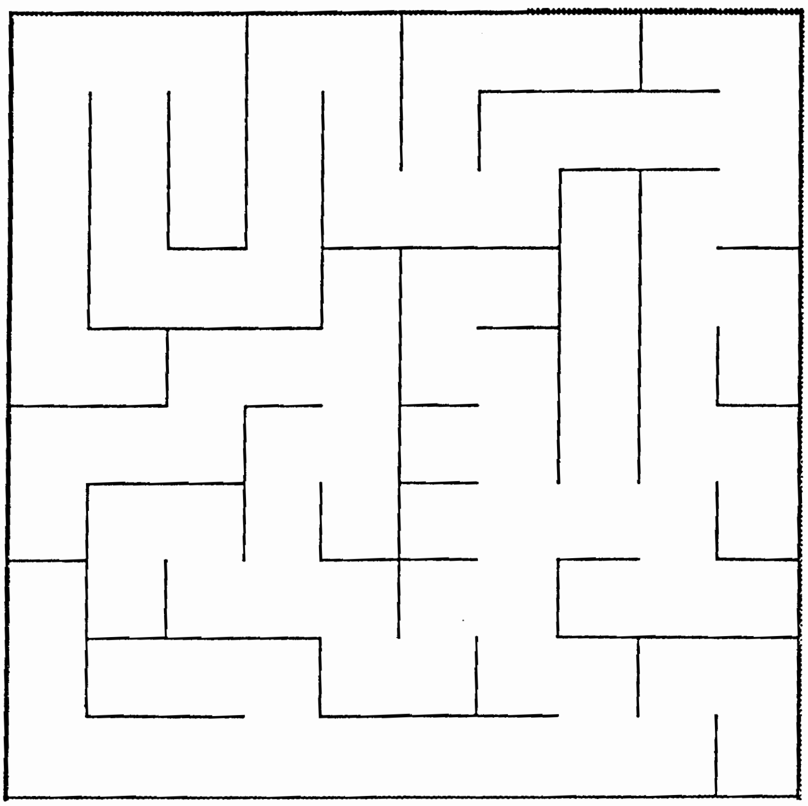
Practice Maze



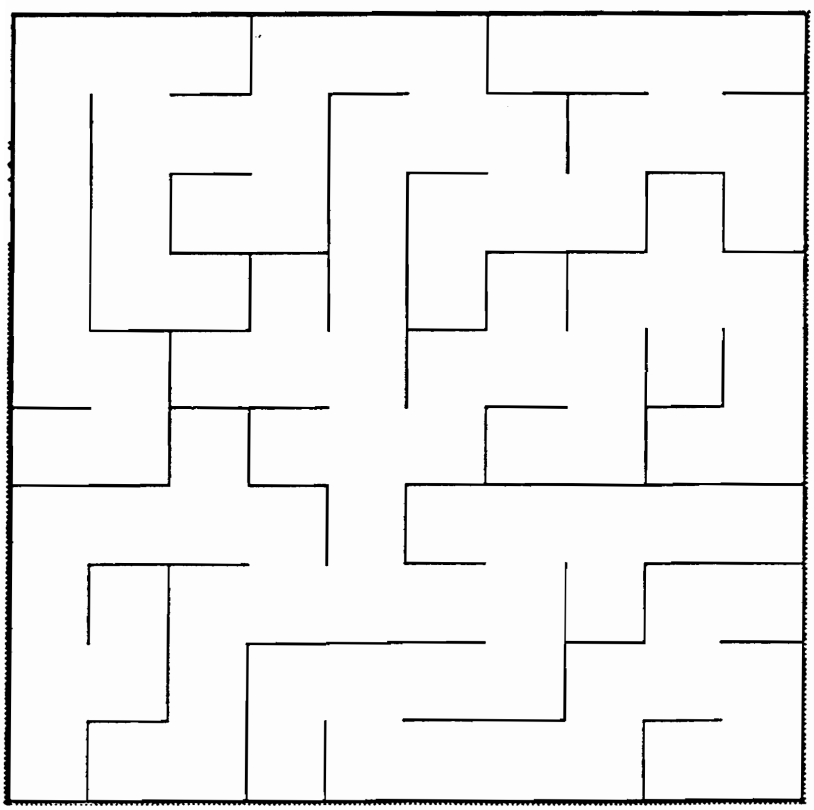
MAZE 1



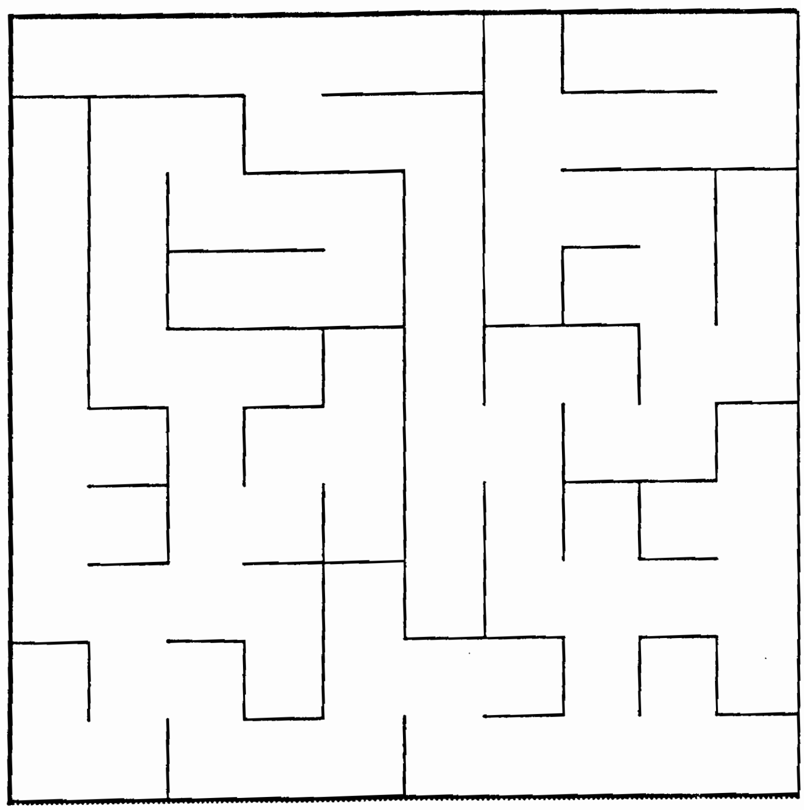
Maze 2



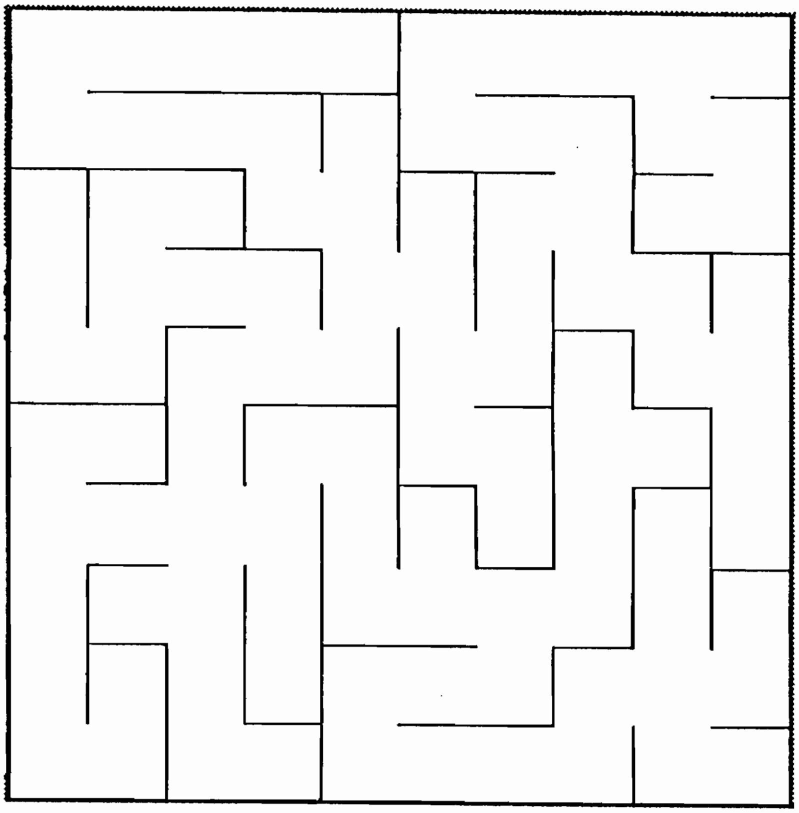
MAZE 3



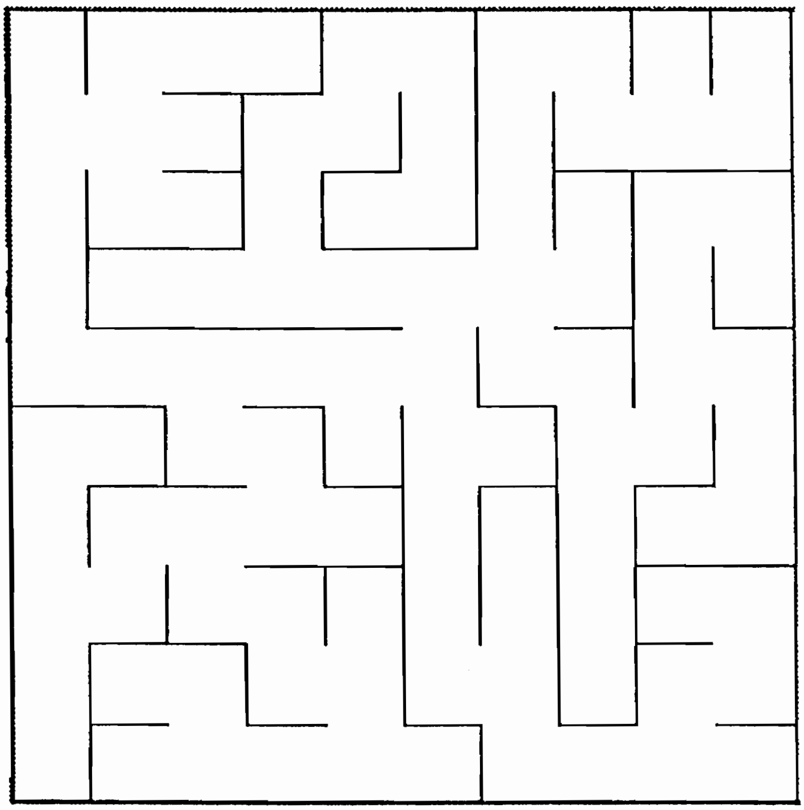
Maze 4



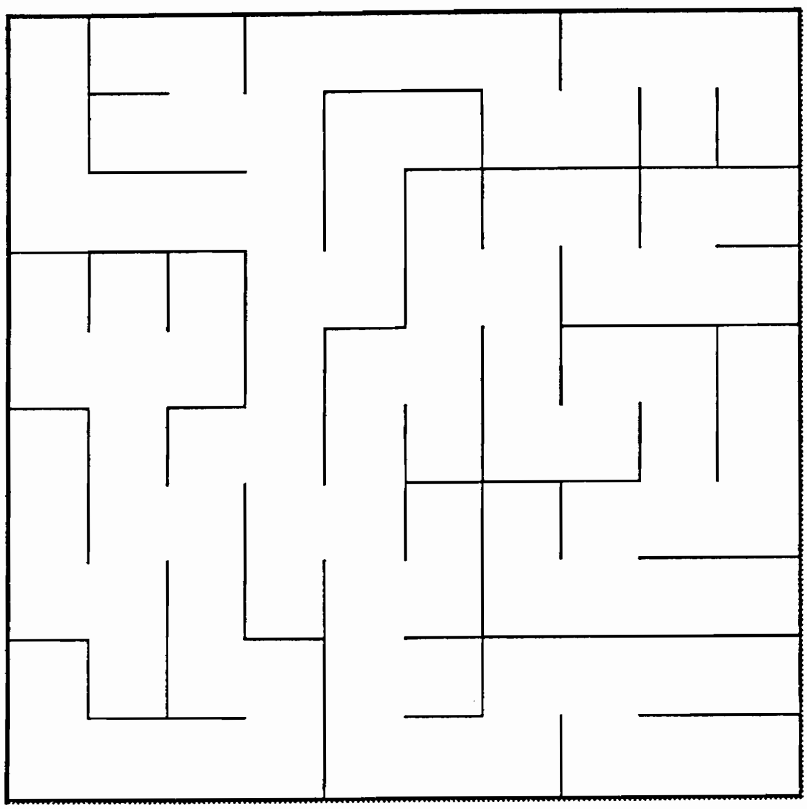
Maze 5



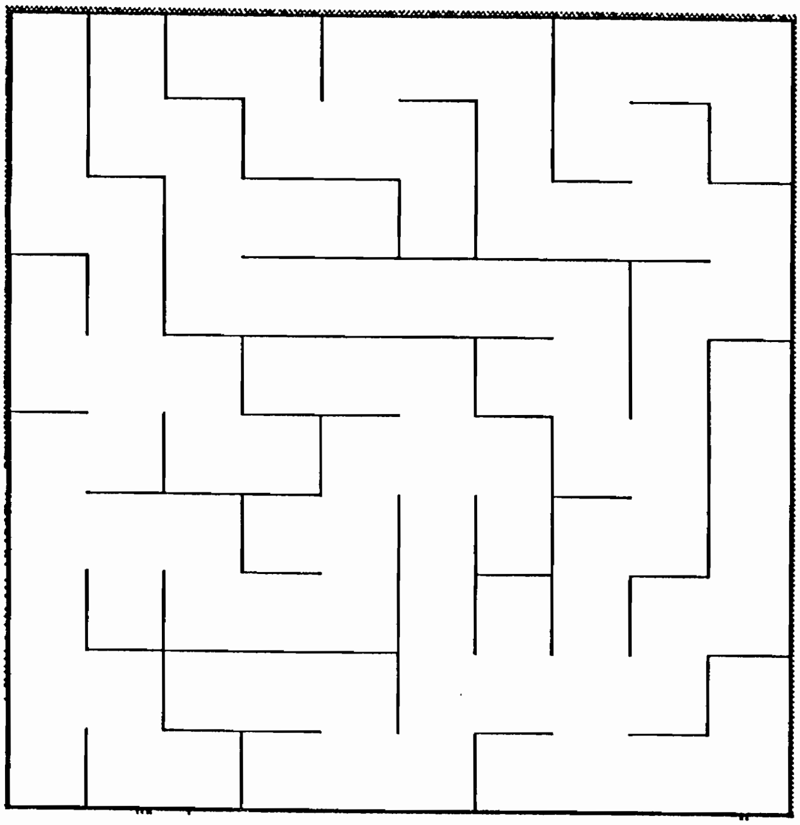
Maze 6



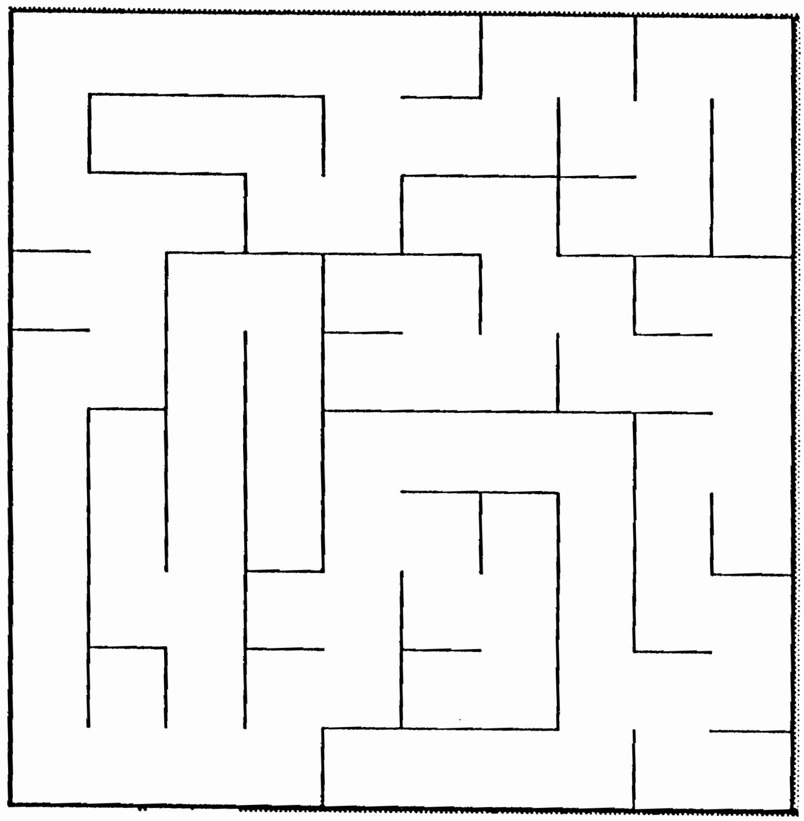
Maze 7



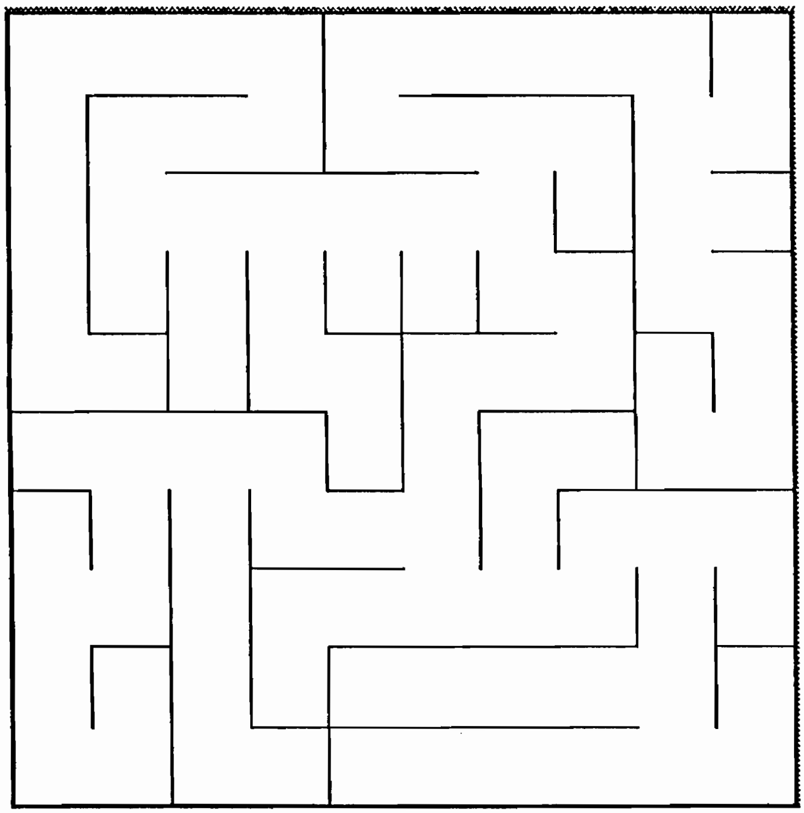
MAZE 8



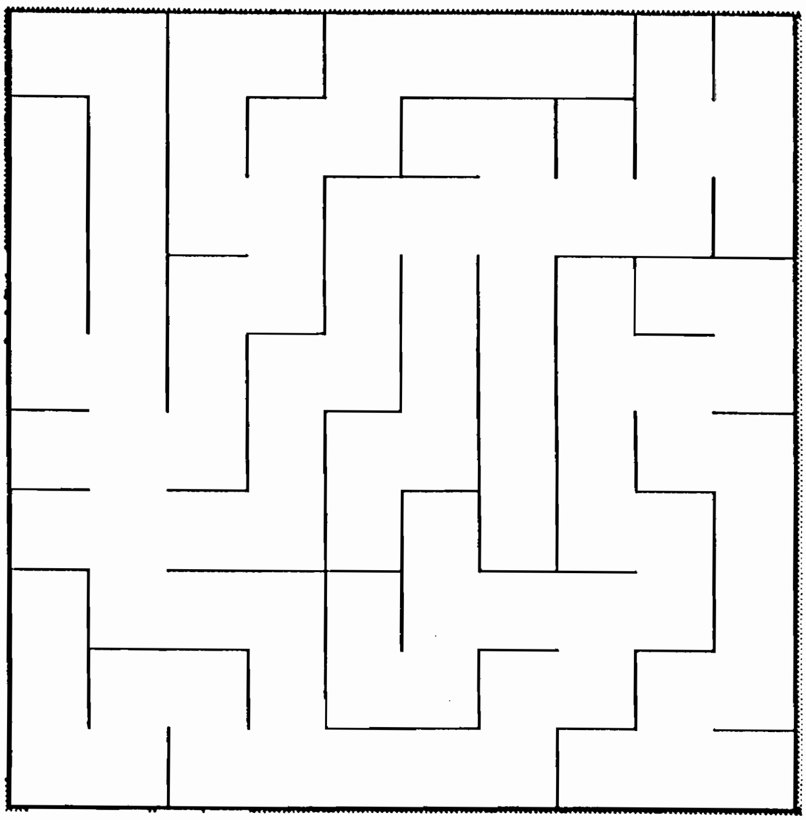
MAZE 9



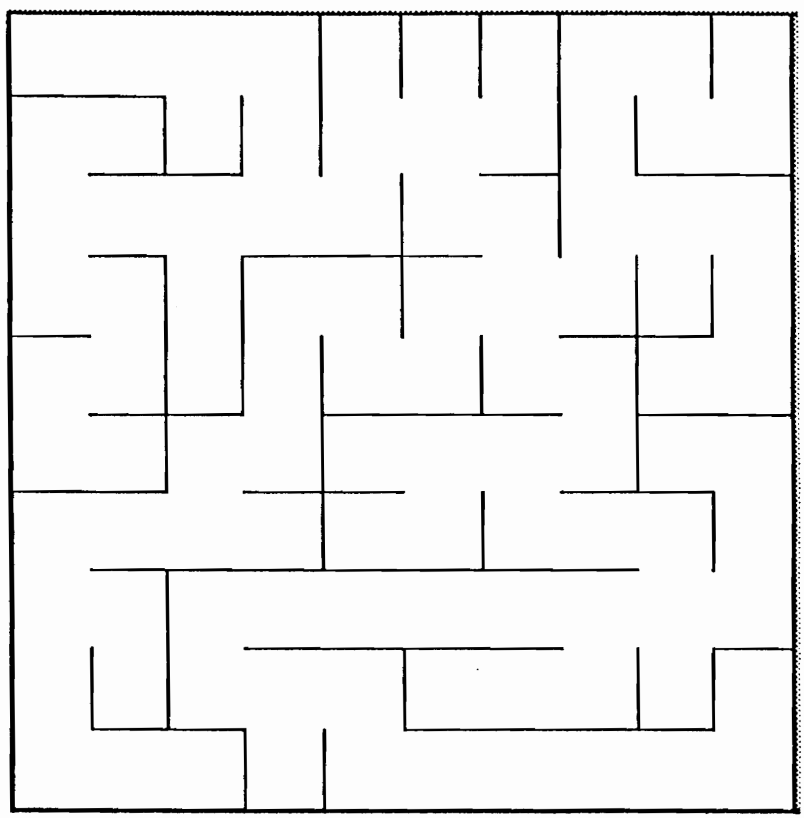
MAZE 10



MAZE 11



Maze 12



APPENDIX B

Informed Consent Form

VIRGINIA POLYTECHNIC INSTITUTE AND STATE UNIVERSITY

Informed Consent for Participants of Investigative Projects

Title of Project: Intelligent Vehicle Highway System Information Display for In-vehicle Routing and Navigation Systems

Principal Investigator: Carolyn A. Bussi

I. THE PURPOSE OF THIS RESEARCH

You are invited to participate in a research project designed to determine the best way to design a navigation guidance system for automobiles. The overall purpose of this study is to evaluate different ways to present navigational information. This research project contains no tricks or deceptions. We are simply interested in how well people are able to use each of the different systems.

II. PROCEDURES

The procedures to be used in this research are as follows. The experiment will consist of a screening session (about a half hour) and an experimental session which will take approximately two hours. If you wish to become a participant after reading the description of the study and signing this form, you will begin with a screening process which involves checking your vision and spatial ability. The purpose of the screening is to determine whether your vision and your level of spatial ability match the levels we are looking for.

First, you will read and sign an informed consent form. The first screening test will measure spatial ability using the Cube Comparisons Test. To continue, your score on the spatial ability test must fall within one of two ranges that we have divided the groups into. Then, your vision will be tested with a Stereo Optical OPTEC™ 2000 vision tester. To continue, visual acuity must be at least 20/40 with correction. Next, your color perception will be tested with Pseudo-Isochromatic Plates. To continue, you must have not have any color deficiencies. Then, if qualified, you may participate in a research experiment which will evaluate different ways to present navigational information. The following is what you will be doing during this study:

DAY 1:

1. Read task instructions.
2. Practice on simulator.
3. Complete test sessions and questionnaires.

The risks or discomforts to which you will be exposed in this experiment are negligible. Also, realize that the initial vision tests are not designed to assess or diagnose any physiological or anatomical vision problem. The tests will be used to determine whether or not you will be able to continue to the main part of the experiment.

III. BENEFITS OF THIS RESEARCH

Your participation in this project will provide us with information that will be used to improve the design of new automobile navigational systems. The ultimate goal of this research is to improve the safety and efficiency of the route guidance in automobiles. This experiment represents a small step in the pursuit of such a goal. It is expected that the results of this study will lead to further topics of research which will continue to improve driving safety for all road users.

study. There may also be certain circumstances under which the investigator may determine that you should not continue as a participant of this project. These include, but are not limited to, unforeseen health-related difficulties, inability to perform the task, and unforeseen danger to the participant, experimenter, or equipment.

VII. APPROVAL OF RESEARCH

This research project has been approved, as required, by the Institutional Review Board for projects involving human participants at Virginia Polytechnic Institute and State University, by the Department of Industrial and Systems Engineering.

VIII.PARTICIPANT'S RESPONSIBILITIES

I know of no reason I cannot participate in this study. I have the following responsibilities:

1. To perform the tasks according to the instructions to the best of my ability.

2. To notify the experimenter at any time about discomfort or desire to discontinue participation.

I have read and understand the scope of this research project as well as my rights. I have no further questions at this time and agree to participate in this study.

Subject's Signature: ______________________________ Researcher's Signature: ____________________

Date: ______________________________ Date: ____________________

IX. PARTICIPANT'S PERMISSION

I have read and understand the informed consent and conditions of this project. All the questions that I have asked have been answered to my satisfaction. I hereby acknowledge the above and give my voluntary consent for participation in this project.

If I participate, I may withdraw at any time without penalty. I agree to abide by the rules of this project.

Should I have any questions about this research or its conduct, I will contact:

Carolyn A. Bussi	231-5359
Investigator	phone
Dr. John G. Casali	231-5073
Faculty Advisor	phone
Ernest R. Stout	231-9359
Chair, IRB	phone
Research Division	

APPENDIX C

Cube Comparisons Spatial Ability Test

CUBE COMPARISONS SPATIAL ABILITY TEST

Name ____

CUBE COMPARISONS TEST — S-2 (Rev.)

Wooden blocks such as children play with are often cubical with a different letter, number, or symbol on each of the six faces (top, bottom, four sides). Each problem in this test consists of drawings of pairs of cubes or blocks of this kind. Remember, there is a different design, number, or letter on each face of a given cube or block. Compare the two cubes in each pair below.

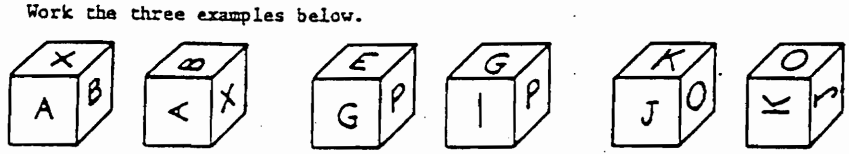
S ☐ D ■   S ■ D ☐

The first pair is marked D because they must be drawings of <u>different</u> cubes. If the left cube is turned so that the A is upright and facing you, the N would be to the left of the A and hidden, not to the right of the A as is shown on the right hand member of the pair. Thus, the drawings must be of different cubes.

The second pair is marked S because they could be drawings of the same cube. That is, if the A is turned on its side the X becomes hidden, the B is now on top, and the C (which was hidden) now appears. Thus the two drawings could be of the same cube.

<u>Note</u>: No letters, numbers, or symbols appear on more than one face of a given cube. Except for that, <u>any</u> letter, number or symbol can be on the hidden faces of a cube.

Work the three examples below.



S ☐ D ☐   S ☐ D ☐   S ☐ D ☐

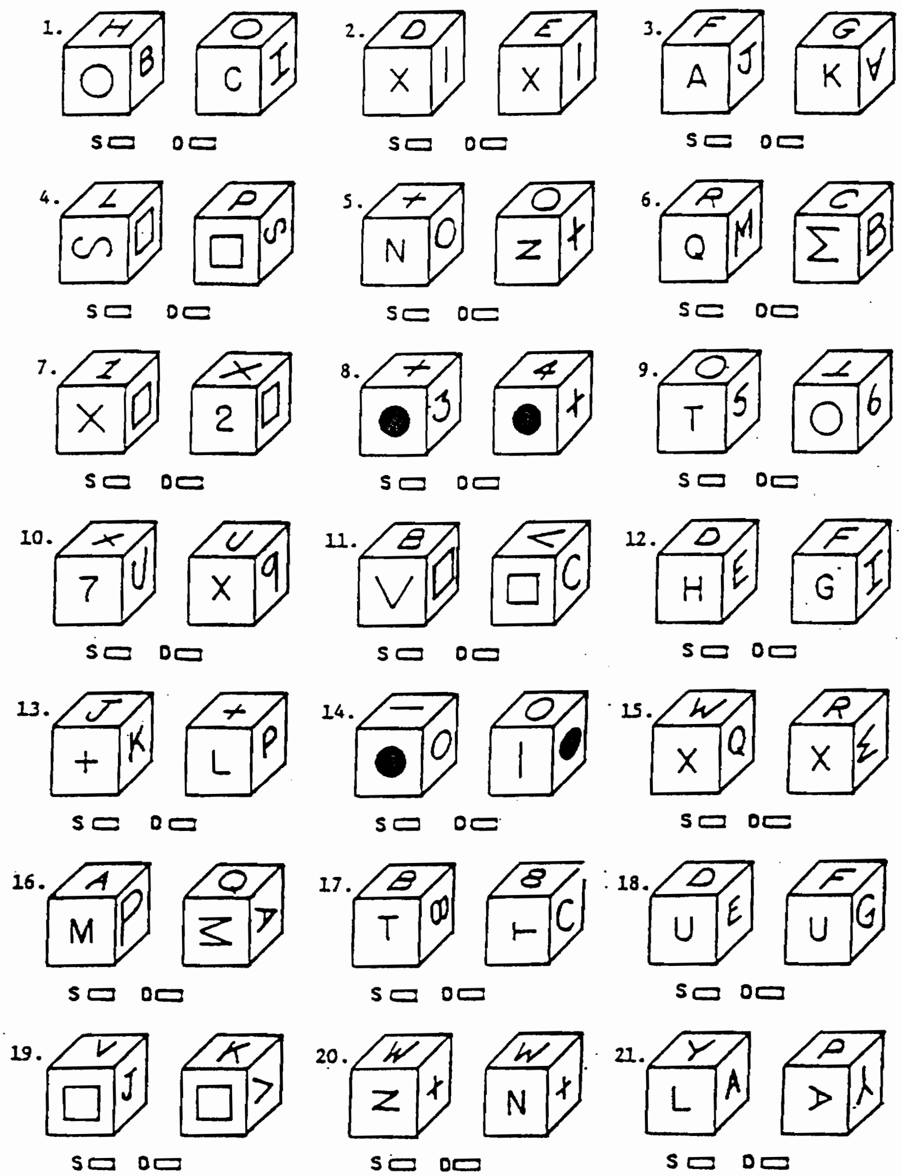
The first pair immediately above should be marked D because the X cannot be at the peak of the A on the left hand drawing and at the base : the A on the right hand drawing. The second pair is "different" because P has its side next to G on the left hand cube but its top next to G on the right hand cube. The blocks in the third pair are the same, the J and K are just turned on their side, moving the O to the top.

Your score on this test will be the number marked correctly minus the number marked incorrectly. Therefore, it will <u>not</u> be to your advantage to guess unless you have some idea which choice is correct. Work as quickly as you can without sacrificing accuracy.

You will have <u>3 minutes</u> for each of the two parts of this test. Each part has one page. When you have finished Part 1, STOP.

DO NOT TURN THE PAGE UNTIL YOU ARE ASKED TO DO SO.

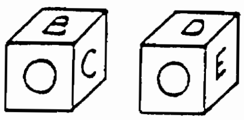
Part 1 (3 minutes)



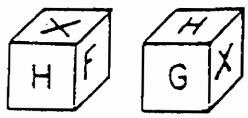
DO NOT GO ON TO THE NEXT PAGE UNTIL ASKED TO DO SO.

STOP.

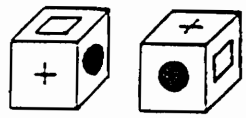
Part 2 (3 minutes)

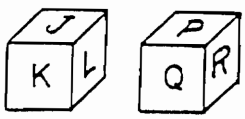
22.


S ☐ D ☐

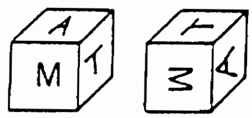
23.


S ☐ D ☐

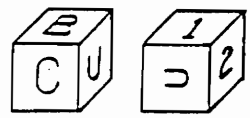
24.

S ☐ D ☐

25.


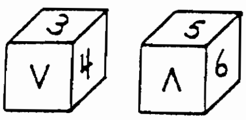
S ☐ D ☐

26.


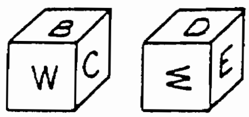
S ☐ D ☐

27.


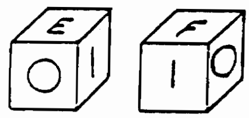
S ☐ D ☐

28.


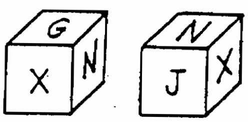
S ☐ D ☐

29.


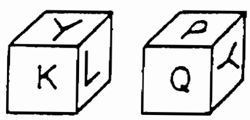
S ☐ D ☐

30.


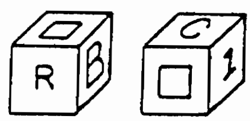
S ☐ D ☐

31.


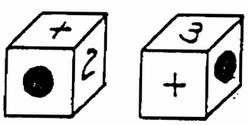
S ☐ D ☐

32.


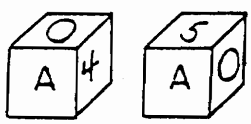
S ☐ D ☐

33.


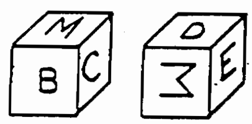
S ☐ D ☐

34.


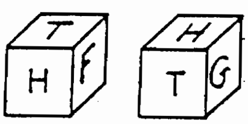
S ☐ D ☐

35.


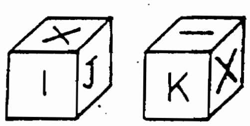
S ☐ D ☐

36.


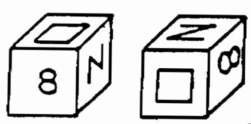
S ☐ D ☐

37.


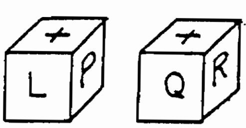
S ☐ D ☐

38.


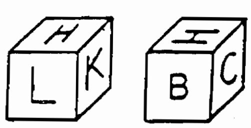
S ☐ D ☐

39.


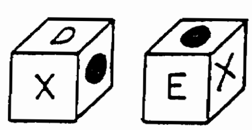
S ☐ D ☐

40.


S ☐ D ☐

41.


S ☐ D ☐

42.


S ☐ D ☐

DO NOT GO BACK TO PART 1 AND

DO NOT GO ON TO ANY OTHER TEST UNTIL ASKED TO DO SO.

STOP.

APPENDIX D

Task Instructions

TASK INSTRUCTIONS

In this study you will be asked to use a computer maze that simulates a navigational environment. You will be asked to sit in front of a computer where you will play the maze game. While the experiment is being run, you will complete twelve (12) conditions with navigational information given in various ways: a map, visual text instructions, or auditory directions.

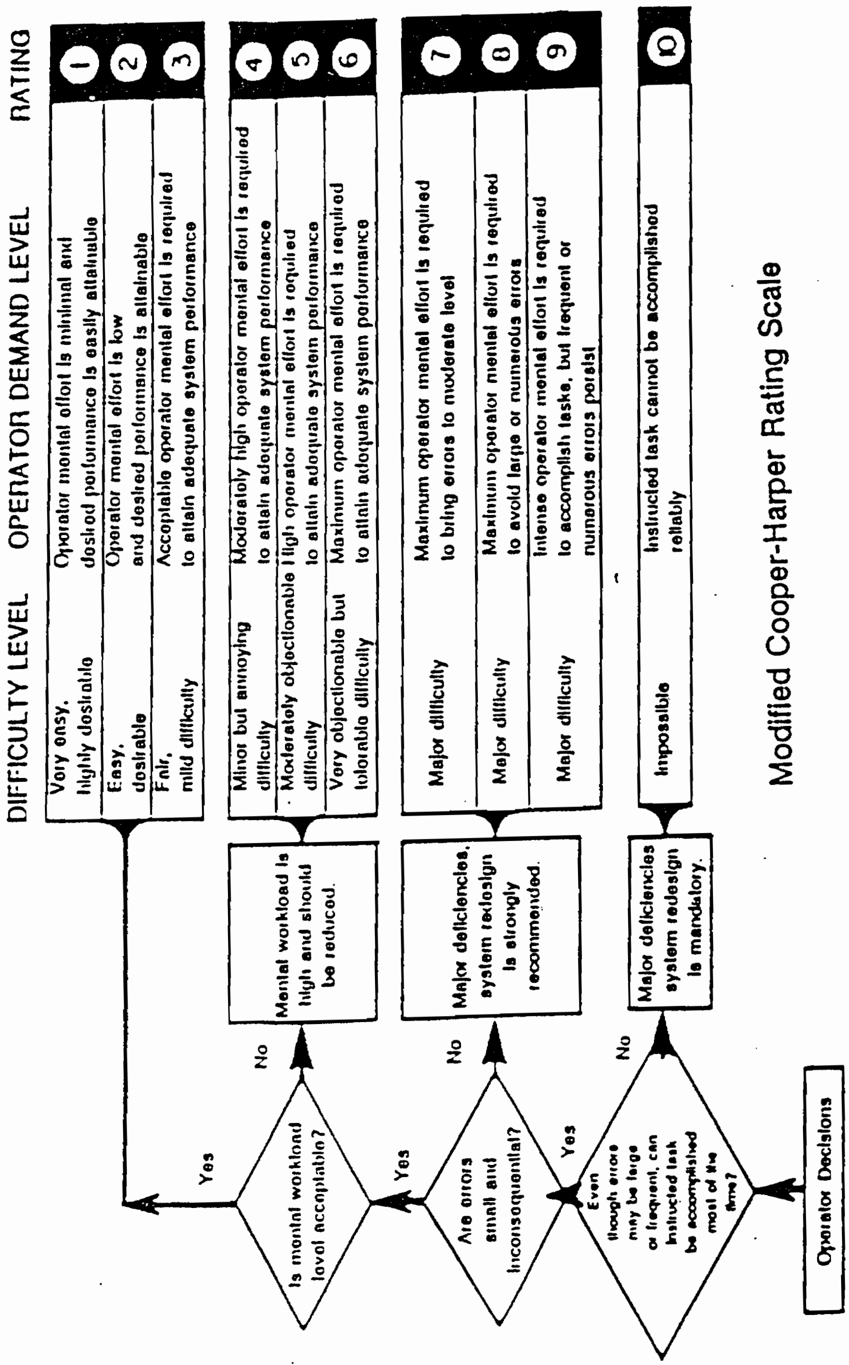
Please remember that both speed and accuracy are important, so try to get to the destination as quickly as possible while bumping into as few walls as possible. You will first be given time to practice with the game. Only after you feel comfortable using the game will the experiment begin (you do not need to feel as if you have mastered the game).

After each scenario, you will be asked to complete a workload questionnaire for that condition just run. After all scenarios are completed, you will be asked to fill out a preference questionnaire.

If you have any questions, please ask the experimenter now.

APPENDIX E

Modified Cooper-Harper Scale



Modified Cooper-Harper Rating Scale

APPENDIX F

Modified Cooper-Harper Scale Instructions

MODIFIED COOPER-HARPER SCALE INSTRUCTIONS

Overview

After each of the following maze scenarios, you will be asked to give a rating on a Modified Cooper-Harper Scale for workload. This rating scale and important definitions for using the scale are shown on the sample which I have given to you. Before you complete any scenarios, we will review:

The definition of the terms used in the scale,

1. The steps you should follow in making you rating on the scale, and
2. How you should think of the ratings.

If you have any questions as we review these points please feel free to ask me.

Important Definitions

To understand and use the Modified Cooper-Harper Scale properly, it is important that you understand the terms used on the scale and how they apply in the context of this experiment.

First, "instructed task" is the maze scenario task you have been assigned to perform in this experiment. It includes moving through the maze as quickly and accurately as possible while receiving navigational guidance from various aids.

Second, the "operator" in this situation is you. Because the scale can be used in different situations, the person performing the ratings is called an operator. You will be operating the system and then using the rating scale to quantify your experience.

Third, the "system" is the complete group of equipment you will be using in performing the instructed task. Together you and the system make up the "operator/system". (For the present experiment, the system is composed of the maze environment, the navigational guidance system, and the joystick controller.)

Fourth, "errors" include any of the following: mistakes, incorrect actions or responses, blunders, and incompletions. In other words, errors are any appreciable deviation from desired "operator/system" performance.

Finally, "mental workload" is the integrated mental effort required to perform the instructed task. In includes such factors as level of attention, depth of thinking, and level of concentration required by the instructed task.

Rating Scale Steps

On the Modified Cooper-Harper Scale you will notice that there is a series of decision which follow a predetermined logical sequence. This logic sequence is designed to help you make more consistent and accurate ratings. Thus, you should follow the logic sequence on the scale for each of your ratings in the experiment.

The steps which you will follow in using the rating scale logic are as follows:

1. First you will decide if the instructed task can be accomplished most of the time; if not, then your rating is a 10 and you should circle the 10 on the rating scale.
2. Second, you will decide if adequate performance is attainable. Adequate performance means that the errors are small and

inconsequential in performing the instructed task. Adequate performance is defined in the set of instructions you have been given for the experimental task. If the errors are not small and inconsequential, then there are major deficiencies in the system and you should proceed to the right. By reading the descriptions associated with the numbers 7, 8, and 9, you should be able to select the one that best describes the situation you have experienced. You would then circle the most appropriate number.

3. If adequate performance is attainable your next decision is whether or not your mental workload for the instructed task is acceptable. If it is not acceptable, you should select a rating of 4, 5, or 6. One of these three ratings should describe the situation you have experienced, and you would circle the most appropriate number.
4. If mental workload is acceptable, you should then move to one of the top three descriptions on the scale. You would read and carefully select the rating 1, 2, or 3 based on the corresponding description that best describes the situation you have experienced. You would circle the most appropriate number.

Remember you are to circle only one number, and the number should be arrived at by following the logic of the scale. You should always begin at the lower left and follow the logic path until you have decided on a rating. In particular, do not skip any steps in the logic. Otherwise, you rating may not be valid and reliable.

How You Should Think of the Rating

Before you begin making ratings there are several points that need to be emphasized. First, be sure to try to perform the instructed task as instructed and make all your evaluations within the context of the instructed task. Try to maintain adequate performance as specified for your task.

Second, the rating scale is not a test of your personal skill. On all of your ratings, you will be evaluating the system for a general user population, not yourself. You may assume you are an experienced member of that population. You should make the assumption that problems you encounter are not problems you created. They are problems created by the system and the instructed task. In other words, don't blame yourself if the system is deficient, blame the system.

Third, try to avoid the problem of nit picking an especially good system, and of saying that a system which is difficult to use is not difficult to use at all. These problems can result in similar ratings for systems with quite different characteristics. Also, try not to overreact to small changes in the system. This can result in ratings which are extremely different when the systems themselves are quite similar. Thus, to avoid any problems, just always try to "tell it like it is" in making your ratings.

If you have any questions, please ask the experimenter at this time.

APPENDIX G

Subjective Preference Questionnaire

SUBJECTIVE PREFERENCE QUESTIONNAIRE

For each pair of navigational aids, circle the one you would prefer to use.

map only	voice only
map only	text only
map only	map and voice
map only	map and text
map only	voice and text
voice only	text only
voice only	map and voice
voice only	map and text
voice only	voice and text
text only	map and voice
text only	map and text
text only	voice and text
map and voice	map and text
map and voice	voice and text
map and text	voice and text

APPENDIX H

Performance and Subjective Workload Questionnaire Data

SUBJECT 1

Subject	Gender (0=male, 1=female)	Spatial ability (0=low, 1=high)	Maze	Collisions	Nav Errors	Time(s)	Workload score
1	0	1	2	2	2	73	6
1	0	1	4	2	1	33	4
1	0	1	6	1	1	34	2
1	0	1	8	5	2	71	4
1	0	1	10	1	0	40	1
1	0	1	12	1	0	48	1
1	0	1	1	0	0	37	3
1	0	1	3	0	0	48	4
1	0	1	5	2	1	37	2
1	0	1	7	2	0	38	3
1	0	1	9	1	1	50	3
1	0	1	11	3	0	49	3

SUBJECT 2

Subject	Gender (0=male, 1=female)	Spatial ability (0=low, 1=high)	Maze	Collisions	Nav Errors	Time(s)	Workload score
2	0	1	2	1	2	59	3
2	0	1	4	1	0	40	3
2	0	1	6	0	1	36	3
2	0	1	8	0	0	57	3
2	0	1	10	0	0	45	2
2	0	1	12	4	1	86	3
2	0	1	1	0	0	39	4
2	0	1	3	3	1	55	6
2	0	1	5	3	0	43	6
2	0	1	7	0	0	47	5
2	0	1	9	0	0	60	5
2	0	1	11	0	0	68	6

SUBJECT 3

Subject	Gender (0=male, 1=female)	Spatial ability (0=low, 1=high)	Maze	Collisions	Nav Errors	Time(s)	Workload score
3	0	1	2	1	0	47	2
3	0	1	4	1	1	39	2
3	0	1	6	2	0	36	2
3	0	1	8	2	0	55	1
3	0	1	10	0	0	41	2
3	0	1	12	2	1	45	3
3	0	1	1	2	0	28	2
3	0	1	3	2	0	47	3
3	0	1	5	1	0	37	3
3	0	1	7	2	0	40	1
3	0	1	9	2	0	52	2
3	0	1	11	2	0	55	3

SUBJECT 4

Subject	Gender (0=male, 1=female)	Spatial ability (0=low, 1=high)	Maze	Collisions	Nav Errors	Time(s)	Workload score
4	0	1	2	2	1	57	4
4	0	1	4	0	0	41	3
4	0	1	6	0	0	35	2
4	0	1	8	0	0	58	3
4	0	1	10	2	0	40	3
4	0	1	12	0	0	47	2
4	0	1	1	1	0	36	6
4	0	1	3	0	0	59	5
4	0	1	5	0	0	45	5
4	0	1	7	0	0	41	4
4	0	1	9	1	1	60	2
4	0	1	11	1	0	57	4

SUBJECT 5

Subject	Gender (0=male, 1=female)	Spatial ability (0=low, 1=high)	Maze	Collisions	Nav Errors	Time(s)	Workload score
5	0	1	2	0	0	52	4
5	0	1	4	0	0	39	4
5	0	1	6	0	0	35	4
5	0	1	8	0	0	53	3
5	0	1	10	2	0	37	2
5	0	1	12	0	0	42	3
5	0	1	1	0	0	28	7
5	0	1	3	0	0	48	9
5	0	1	5	1	0	41	5
5	0	1	7	1	0	40	7
5	0	1	9	0	0	45	7
5	0	1	11	0	0	55	8

SUBJECT 6

Subject	Gender (0=male, 1=female)	Spatial ability (0=low, 1=high)	Maze	Collisions	Nav Errors	Time(s)	Workload score
6	0	1	2	1	1	47	2
6	0	1	4	1	0	37	1
6	0	1	6	1	0	35	3
6	0	1	8	1	0	52	2
6	0	1	10	0	1	36	1
6	0	1	12	1	0	41	1
6	0	1	1	4	2	33	6
6	0	1	3	2	1	40	5
6	0	1	5	1	0	40	4
6	0	1	7	1	0	39	2
6	0	1	9	0	0	46	3
6	0	1	11	1	0	47	3

SUBJECT 7

Subject	Gender (0=male, 1=female)	Spatial ability (0=low, 1=high)	Maze	Collisions	Nav Errors	Time(s)	Workload score
7	0	1	2	5	2	77	2
7	0	1	4	1	0	52	4
7	0	1	6	2	0	45	2
7	0	1	8	0	0	68	3
7	0	1	10	2	0	45	1
7	0	1	12	1	0	66	3
7	0	1	1	1	0	47	3
7	0	1	3	4	0	60	4
7	0	1	5	2	0	48	2
7	0	1	7	6	0	56	3
7	0	1	9	5	0	53	2
7	0	1	11	13	1	127	7

SUBJECT 8

Subject	Gender (0=male, 1=female)	Spatial ability (0=low, 1=high)	Maze	Collisions	Nav Errors	Time(s)	Workload score
8	0	1	2	2	0	44	3
8	0	1	4	4	1	42	3
8	0	1	6	2	1	37	2
8	0	1	8	5	0	53	4
8	0	1	10	1	0	34	1
8	0	1	12	0	0	43	2
8	0	1	1	4	1	30	4
8	0	1	3	3	0	46	3
8	0	1	5	5	1	34	1
8	0	1	7	40	2	43	4
8	0	1	9	3	0	51	1
8	0	1	11	2	1	51	2

SUBJECT 9

Subject	Gender (0=male, 1=female)	Spatial ability (0=low, 1=high)	Maze	Collisions	Nav Errors	Time(s)	Workload score
9	0	1	2	3	0	58	1
9	0	1	4	0	0	48	2
9	0	1	6	0	0	43	1
9	0	1	8	6	2	81	2
9	0	1	10	3	1	52	1
9	0	1	12	1	1	68	3
9	0	1	1	3	0	42	1
9	0	1	3	1	0	52	1
9	0	1	5	6	0	47	1
9	0	1	7	3	0	46	2
9	0	1	9	1	0	73	3
9	0	1	11	0	0	72	1

SUBJECT 10

Subject	Gender (0=male, 1=female)	Spatial ability (0=low, 1=high)	Maze	Collisions	Nav Errors	Time(s)	Workload score
10	0	1	2	4	0	44	1
10	0	1	4	1	0	36	1
10	0	1	6	2	2	38	3
10	0	1	8	6	0	51	1
10	0	1	10	1	0	34	2
10	0	1	12	1	1	45	3
10	0	1	1	2	0	25	1
10	0	1	3	3	0	42	3
10	0	1	5	1	0	35	3
10	0	1	7	1	1	39	1
10	0	1	9	2	0	43	3
10	0	1	11	0	0	54	3

SUBJECT 11

Subject	Gender (0=male, 1=female)	Spatial ability (0=low, 1=high)	Maze	Collisions	Nav Errors	Time(s)	Workload score
11	0	1	2	2	3	68	5
11	0	1	4	0	0	37	5
11	0	1	6	1	1	34	3
11	0	1	8	3	2	71	5
11	0	1	10	0	0	41	3
11	0	1	12	0	2	55	4
11	0	1	1	2	2	39	5
11	0	1	3	3	1	57	7
11	0	1	5	0	0	35	2
11	0	1	7	5	2	53	6
11	0	1	9	6	2	59	4
11	0	1	11	1	0	58	5

SUBJECT 12

Subject	Gender (0=male, 1=female)	Spatial ability (0=low, 1=high)	Maze	Collisions	Nav Errors	Time(s)	Workload score
12	0	1	2	6	4	66	3
12	0	1	4	6	2	54	2
12	0	1	6	3	1	43	1
12	0	1	8	9	2	75	3
12	0	1	10	4	3	52	2
12	0	1	12	1	0	58	1
12	0	1	1	27	5	106	4
12	0	1	3	1	0	53	3
12	0	1	5	2	0	42	1
12	0	1	7	11	4	124	3
12	0	1	9	5	1	58	2
12	0	1	11	0	0	65	3

SUBJECT 13

Subject	Gender (0=male, 1=female)	Spatial ability (0=low, 1=high)	Maze	Collisions	Nav Errors	Time(s)	Workload score
13	0	1	2	1	2	96	3
13	0	1	4	0	0	50	3
13	0	1	6	1	0	39	3
13	0	1	8	1	0	65	3
13	0	1	10	0	0	48	2
13	0	1	12	2	0	62	1
13	0	1	1	8	10	147	3
13	0	1	3	1	0	59	3
13	0	1	5	1	0	43	2
13	0	1	7	2	0	51	3
13	0	1	9	1	0	67	3
13	0	1	11	0	0	65	2

SUBJECT 14

Subject	Gender (0=male, 1=female)	Spatial ability (0=low, 1=high)	Maze	Collisions	Nav Errors	Time(s)	Workload score
14	0	1	2	6	5	107	8
14	0	1	4	0	0	59	2
14	0	1	6	1	0	45	2
14	0	1	8	0	0	71	2
14	0	1	10	1	0	66	3
14	0	1	12	3	0	70	2
14	0	1	1	5	0	54	5
14	0	1	3	6	2	72	8
14	0	1	5	2	0	58	6
14	0	1	7	0	0	53	5
14	0	1	9	1	0	77	4
14	0	1	11	3	0	87	4

SUBJECT 15

Subject	Gender (0=male, 1=female)	Spatial ability (0=low, 1=high)	Maze	Collisions	Nav Errors	Time(s)	Workload score
15	0	1	2	12	9	168	9
15	0	1	4	1	0	55	5
15	0	1	6	1	0	49	4
15	0	1	8	1	0	75	4
15	0	1	10	0	0	64	2
15	0	1	12	0	0	66	3
15	0	1	1	3	1	64	9
15	0	1	3	4	0	61	7
15	0	1	5	1	0	50	3
15	0	1	7	1	0	61	8
15	0	1	9	0	0	78	3
15	0	1	11	0	0	76	4

SUBJECT 16

Subject	Gender (0=male, 1=female)	Spatial ability (0=low, 1=high)	Maze	Collisions	Nav Errors	Time(s)	Workload score
16	0	1	2	2	0	87	2
16	0	1	4	1	1	63	3
16	0	1	6	1	1	57	7
16	0	1	8	1	0	90	2
16	0	1	10	1	0	72	3
16	0	1	12	0	0	68	2
16	0	1	1	1	0	53	1
16	0	1	3	5	2	79	6
16	0	1	5	1	0	52	5
16	0	1	7	0	0	66	1
16	0	1	9	1	0	92	4
16	0	1	11	0	0	82	4

SUBJECT 17

Subject	Gender (0=male, 1=female)	Spatial ability (0=low, 1=high)	Maze	Collisions	Nav Errors	Time(s)	Workload score
17	0	1	2	12	6	130	2
17	0	1	4	3	1	71	2
17	0	1	6	20	5	306	7
17	0	1	8	12	5	139	2
17	0	1	10	2	2	63	1
17	0	1	12	0	2	83	1
17	0	1	1	161	3	113	3
17	0	1	3	9	4	98	7
17	0	1	5	6	3	129	3
17	0	1	7	4	4	143	3
17	0	1	9	4	0	87	1
17	0	1	11	13	3	137	5

SUBJECT 18

Subject	Gender (0=male, 1=female)	Spatial ability (0=low, 1=high)	Maze	Collisions	Nav Errors	Time(s)	Workload score
18	0	1	2	8	4	61	3
18	0	1	4	5	0	38	2
18	0	1	6	6	3	42	2
18	0	1	8	3	0	59	3
18	0	1	10	2	0	38	1
18	0	1	12	2	0	43	3
18	0	1	1	5	2	30	4
18	0	1	3	14	4	49	3
18	0	1	5	6	2	40	2
18	0	1	7	5	2	45	4
18	0	1	9	5	0	51	1
18	0	1	11	8	0	54	3

SUBJECT 19

Subject	Gender (0=male, 1=female)	Spatial ability (0=low, 1=high)	Maze	Collisions	Nav Errors	Time(s)	Workload score
19	0	1	2	0	2	77	5
19	0	1	4	0	0	57	2
19	0	1	6	0	0	48	1
19	0	1	8	2	0	85	3
19	0	1	10	0	0	60	2
19	0	1	12	0	0	64	1
19	0	1	1	0	0	48	5
19	0	1	3	2	0	64	5
19	0	1	5	0	0	53	4
19	0	1	7	0	0	51	3
19	0	1	9	0	0	84	4
19	0	1	11	0	0	78	4

SUBJECT 20

Subject	Gender (0=male, 1=female)	Spatial ability (0=low, 1=high)	Maze	Collisions	Nav Errors	Time(s)	Workload score
20	0	1	2	4	0	52	1
20	0	1	4	0	0	46	2
20	0	1	6	1	0	44	2
20	0	1	8	1	0	68	2
20	0	1	10	0	0	45	2
20	0	1	12	0	0	49	1
20	0	1	1	2	1	29	2
20	0	1	3	3	0	46	3
20	0	1	5	0	0	48	3
20	0	1	7	1	0	55	3
20	0	1	9	1	0	64	3
20	0	1	11	2	0	63	3

SUBJECT 21

Subject	Gender (0=male, 1=female)	Spatial ability (0=low, 1=high)	Maze	Collisions	Nav Errors	Time(s)	Workload score
21	0	1	2	3	2	59	4
21	0	1	4	0	0	39	3
21	0	1	6	11	7	270	7
21	0	1	8	0	2	71	2
21	0	1	10	0	0	42	2
21	0	1	12	1	1	56	3
21	0	1	1	2	0	37	4
21	0	1	3	2	1	45	4
21	0	1	5	1	0	40	2
21	0	1	7	3	3	52	3
21	0	1	9	2	0	57	3
21	0	1	11	0	0	64	4

SUBJECT 22

Subject	Gender (0=male, 1=female)	Spatial ability (0=low, 1=high)	Maze	Collisions	Nav Errors	Time(s)	Workload score
22	0	1	2	0	0	56	1
22	0	1	4	1	0	45	2
22	0	1	6	1	1	40	2
22	0	1	8	3	2	59	4
22	0	1	10	0	0	41	2
22	0	1	12	0	0	48	1
22	0	1	1	0	0	32	1
22	0	1	3	4	1	57	6
22	0	1	5	2	1	46	5
22	0	1	7	0	0	41	2
22	0	1	9	1	0	57	3
22	0	1	11	1	1	55	2

SUBJECT 23

Subject	Gender (0=male, 1=female)	Spatial ability (0=low, 1=high)	Maze	Collisions	Nav Errors	Time(s)	Workload score
23	0	1	2	3	1	85	3
23	0	1	4	0	0	51	2
23	0	1	6	0	0	47	3
23	0	1	8	0	0	85	2
23	0	1	10	0	0	64	2
23	0	1	12	1	0	64	3
23	0	1	1	3	2	62	4
23	0	1	3	0	0	59	5
23	0	1	5	0	0	49	2
23	0	1	7	3	0	61	5
23	0	1	9	0	0	79	2
23	0	1	11	1	0	80	2

SUBJECT 24

Subject	Gender (0=male, 1=female)	Spatial ability (0=low, 1=high)	Maze	Collisions	Nav Errors	Time(s)	Workload score
24	0	1	2	3	3	70	2
24	0	1	4	1	0	41	1
24	0	1	6	3	2	75	10
24	0	1	8	1	0	70	2
24	0	1	10	2	0	54	1
24	0	1	12	1	0	56	3
24	0	1	1	4	0	45	2
24	0	1	3	2	0	46	1
24	0	1	5	2	0	45	2
24	0	1	7	3	1	60	3
24	0	1	9	1	4	66	2
24	0	1	11	1	0	71	3

APPENDIX I

Frequency of Preference Data

FREQUENCY OF PREFERENCE DATA FOR ALL SUBJECTS BY GENDER

Female					
	map	voice	text	map&voice	map&text
map	xxx	6	5	0	1
voice	6	xxx	8	3	5
text	7	4	xxx	2	4
map&voice	12	9	10	xxx	9
map&text	11	7	8	3	xxx
voice&text	8	7	8	4	6
Male					
	map	voice	text	map&voice	map&text
map	xxx	6	8	1	5
voice	6	xxx	8	1	7
text	4	4	xxx	1	1
map&voice	11	11	11	xxx	9
map&text	7	5	11	3	xxx
voice&text	7	7	10	0	6

FREQUENCY OF PREFERENCE DATA FOR ALL SUBJECTS BY SPATIAL ABILITY

High Spatial Ability					
	map	voice	text	map&voice	map&text
map	xxx	7	7	0	3
voice	5	xxx	8	3	5
text	5	4	xxx	2	3
map&voice	12	9	10	xxx	8
map&text	9	7	9	4	xxx
voice&text	8	8	10	2	6
Low Spatial Ability					
	map	voice	text	map&voice	map&text
map	xxx	5	6	1	3
voice	7	xxx	8	1	7
text	6	4	xxx	1	2
map&voice	11	11	11	xxx	10
map&text	9	5	10	2	xxx
voice&text	7	6	8	2	6

FREQUENCY OF PREFERENCE DATA FOR ALL SUBJECTS BY GENDER/SPATIAL ABILITY

Female					
High Spatial Ability					
	map	voice	text	map&voice	map&text
map	xxx	4	3	0	1
voice	2	xxx	5	3	2
text	3	1	xxx	2	2
map&voice	6	3	4	xxx	4
map&text	5	4	4	2	xxx
voice&text	4	4	4	2	3
Low Spatial Ability					
	map	voice	text	map&voice	map&text
map	xxx	2	2	0	0
voice	4	xxx	3	0	3
text	4	3	xxx	0	2
map&voice	6	6	6	xxx	5
map&text	6	3	4	1	xxx
voice&text	4	3	4	2	3

Male					
High Spatial Ability					
	map	voice	text	map&voice	map&text
map	xxx	3	4	0	2
voice	3	xxx	3	0	3
text	2	3	xxx	0	1
map&voice	6	6	6	xxx	4
map&text	4	3	5	2	xxx
voice&text	4	4	6	0	3
Low Spatial Ability					
	map	voice	text	map&voice	map&text
map	xxx	3	4	1	3
voice	3	xxx	5	1	4
text	2	1	xxx	1	0
map&voice	5	5	5	xxx	5
map&text	3	2	6	1	xxx
voice&text	3	3	4	0	3

VITA

Carolyn Ann Bussi was born on May 10, 1966 in Buffalo, New York. She received her Bachelor of Science degree in Industrial Engineering from the State University of New York at Buffalo in May 1989. While pursuing her Master of Science degree in Industrial Engineering at the State University of New York at Buffalo, she worked at the University Computing Center as the graduate supervisor of computer consultants and a documentation specialist writing software helps and tutorials for all computing systems on campus. During her Master's degree, she also spent almost a year at IBM in Poughkeepsie, New York doing software interface design and prototyping graphical user interfaces for large scale systems. Her Master's thesis focused on designer's behavior in procedural and creative design and she completed her Master's degree in May, 1992. She entered into the Ph.D. program at Virginia Polytechnic Institute and State University (Virginia Tech) in August, 1991. While at Virginia Tech she worked as both a graduate teaching assistant and a graduate research assistant. Her graduate teaching assistant assignments included undergraduate (Introduction to Industrial and Systems Engineering, Introduction to Human Factors Engineering, and Engineering Economy) and graduate courses (Applied Human Factors Engineering). She worked with Dr. Jeffrey C. Woldstad on a grant for the Association of American Railroads and a grant for Intelligent Transportation Systems. She is a member of Alpha Pi Mu as well as the Human Factors and Ergonomics Society, the Ergonomics Society, the American Association for Engineering Education, and the Institute for Industrial Engineers. She will be working at the Eastman Kodak Company in Rochester, New York.

Carolyn Ann Bussi

Carolyn Ann Bussi