

2008

Reducing Cognitive Load Using Hypervariate Display

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Reducing Cognitive Load Using Hypervariate Display

by

William M. Garrabrants

A dissertation submitted in partial fulfillment of the requirements for the degree of
Doctor of Philosophy
in
Computer Information Systems

Graduate School of Computer and Information Sciences
Nova Southeastern University

2008

We hereby certify that this dissertation, submitted by William M. Garrabrants, conforms to acceptable standards and is fully adequate in scope and quality to fulfill the dissertation requirements for the degree of Doctor of Philosophy.

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Graduate School of Computer and Information Sciences
Nova Southeastern University

2008

An Abstract of a Dissertation Submitted to Nova Southeastern University
in Partial Fulfillment of the Requirements for the Degree of Doctor of Philosophy

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William M. Garrabrants

November 2008

This research examined the application of hypervariate display principles to human-computer interfaces with the intent of reducing the cognitive load placed on the operator during high-intensity activity. This research extended the existing body of knowledge relevant to reducing the cognitive load using human-computer interfaces. Existing research has explored the application of techniques that, when used in isolation, contribute to a computer operator's understanding of the data or efficiency in execution of tasks. This research studied the collaborative use of proven display techniques to improve a computer operator's ability to understand large amounts of data more rapidly and react to that data more effectively. These techniques, including the display of multiple variables in a single window, use of preattentive factors in the display, and the severing of geospatial dependencies on data significantly contributed to the reduction of cognitive burdens placed on a user in environments that are typically overwhelming. Experiments performed on 18 volunteer participants conclusively proved that the hypervariate display improved the participants' ability to handle increased workload, comprehend complex situations quickly and completely, and efficiently respond to the situation in an effective manner. This research has significant value and broad application to user communities where computers are used to control high-intensity operations such as military and law enforcement environments.

Acknowledgments

From an early stage in my life, I received encouragement from my father to get as much education as possible. From his unsolvable algebra problems at the kitchen table to his constant encouragement on my doctorate I have come to appreciate and share his thirst for knowledge. Any project of this enormity requires endurance on the part of the participant, but more importantly requires the patience and encouragement of the participant's family. My father was always an inspiration. This propelled me through my undergraduate and graduate studies. While it has not always been easy and the road has been filled with many challenges, I am grateful for the support of my wife, Marie, and my children Reid, Cara, Scott, and Abbey; they provided the foundation for my daily efforts through their encouragement and prayers.

Next, I am indebted to my committee, Maxine Cohen, Dan Macchiarella, and Bill Hafner. Dr. Cohen was excellent at working as a coach, visionary, and mentor to focus my ideas and words into a polished product. Dr. Macchiarella's insights from the "been there done that" perspective were invaluable to my writing, especially early in the dissertation process. Dr. Hafner was my first professor at Nova Southeastern, and set a positive tone for my entire experience. My sincerest gratitude goes out to them for their guidance and encouragement.

Finally, I wish to recognize some folks at my previous place of employment that were instrumental in making this dissertation happen. There was one person that permitted this study to be an empirical analysis instead of a theoretical discussion – Bill Whitlow. As my supervisor at Titan Corporation, he understood my concepts and permitted the use of a development team to develop the prototype interface at corporate expense. This took my ideas out of the realm of theory and into practical application. The amazing group of software engineers that put up with the design meetings and the constant personal direction from me, and still produced some very elegant and "clean" code have my deepest admiration. Their dedication and skill were evident in their every-day effort, and certainly made the difference for me in this study.

My deepest gratitude to all.

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Chapter 1

Introduction

Background

The military, taking advantage of the increased processing capabilities of the personal computer; has developed sophisticated simulation systems for training and command and control systems for management of an ever-increasingly complex battlefield (Garrabrants, 1998). The increased capacity of these computers is a double-edged sword, however. While they have made automated decision support systems possible, they have begun to deliver more data to the computer operator than can be handled effectively. Military and paramilitary/civilian command, control, communications, and intelligence (C4I) systems rely heavily on large databases and communications of various means to create a “tactical picture” (i.e., a map with disposition of units, supplies, weapons, aircraft, etc.) to gain and maintain situational awareness. The volume and variety of data arriving at the command and control system has begun to overwhelm the very operators that the systems were supposed to help. During combat operations in Iraq in 2003, high-ranking military officers expressed concerns about information overload in battle with the use of command, control, communications, and intelligence systems (Onley, 2003).

Cognitive overload occurs when the capacity of working memory is exceeded and information elements that could be dealt under normal conditions are ignored, misinterpreted, or not recognized (Oostendorp, 2003). In C4I systems, factors such as

steady streams of intelligence information, unit status, logistics issues, and mission assignments (compounded by the immediacy of a battle where lives are at stake) bring so much information to the working memory of the receiver that individual effectiveness not only tapers off, but attention, perception, and memory lose their existing capacity (Krish, 2005). With each additional object that a computer operator has to deal with, more data must be processed in working memory. At some point, the operator's cognitive abilities become saturated, efficiency declines and frustration rises (Waddington, 1996). As the operators of military simulation systems are overwhelmed with data and the demands for higher levels of control become stronger, the potential for cognitive overload becomes much greater.

The impairment of user's cognitive abilities with too much information is not unique to the Department of Defense; overload can occur anywhere that large quantities of varied data exist that must be understood by the user quickly. Air traffic control, commercial aircraft cockpits, emergency response personnel (police, fire, etc.), and even computer game interfaces are examples of how overload applies in many facets of life today.

Under certain circumstances, visually presenting multiple aspects of information simultaneously can increase comprehension and speed up understanding of the information's context. A hypervariate display combines a large number of variables into a display that presents information in a format that is understandable and easy to control. A hypervariate display employs a variety of symbology and visibility characteristics to allow rapid comparisons of disparate objects, allows for local viewing of objects that are

widely separated, and uses filtering to present a focused, actionable display (Spence, 2001).

Problem Statement

There exists a need for improved, efficient methods of delivering important decision-making data to computer operators in order to reduce their cognitive load, improve efficiency, and reduce information processing time. Assessment of this need is based on the researcher's 30 years of experience with the use of C4I systems in a wide variety of environments and evaluation of current literature. Recent warnings of information overload in military operations (Onley, 2003) demonstrate that the volume of information flow is reaching unmanageable levels. At the same time, initiatives like the Tactical Decision Making Under Stress (TADMUS) program (U.S. Navy, 2008) seek to streamline the presentation of existing data to improve the decision making process when faced with a crisis. Further, research in the field of augmented cognition (the use of intelligent interfaces and neurological technology to anticipate bottlenecks that occur when passing information from a graphical user interface and a person) freely acknowledges that cognitive loading will continue to be a concern for computer designers. The challenge is to provide a means of presenting data in a manner that allows the operator to see and understand the data more quickly, process more data in less time, and perform data manipulation more effectively without over stimulating the operator's working memory. This will increase data visibility and decrease processing time. This research, therefore, will examine the influence of combining many decision-making variables into a single display in order to improve operator awareness and efficiency.

Goal

This investigation creates an extension of an existing graphical user interface that employs hypervariate display techniques to reduce the cognitive load placed on system operators of a military wargame. The design concept for the interface extension was to produce a display that provided a view of critical decision-making data and a simple means of performing various commonly used functions. This display increased the capacity of system operators to handle more system objects effectively without increasing the load on the user's working memory. Additionally, the hypervariate display reduced the amount of physical activity such as key clicks, mouse movement, window changes, etc. necessary to control objects, accelerated the accomplishment of tasks and improved visibility of objects for which the operator had direct responsibility. The hypervariate display concepts demonstrated in this research are extensible to a variety of applications such as military and civilian command and control devices, simulation systems, and other display devices that deliver large volumes of diverse information, particularly under time constraints.

Relevance and Significance

Development of a successful conceptual model for dealing with cognitive load has the potential to provide faster, better decisions in a variety of environments. Military and civilian command and control systems rely heavily on large data warehouses and a wide range of communications methods to develop an understanding of an evolving situation. Even newer emergency response organizations such as the Federal Emergency Management Agency (FEMA) and the Department of Homeland Defense are deeply concerned with integration of the various management systems that would be brought to

a terrorist situation or other large incident (FEMA, 2004). Onley's (2003) warning of overburdening of military system operators indicates that visualization techniques that reduce the complexity of data that is presented to military, civilian or government agency operators would be of great value.

Paramilitary/civilian command centers have similar information processing requirements to the military, from fire stations, to police command centers, to drug enforcement control centers (Chen, et al., 2003). The potential for a flood of information in civilian command centers exists as a result of riots, major conflagrations, natural disasters, terrorist events, and other major civil disturbances. Local leaders and emergency response personnel are ill prepared or equipped to deal with the inundation of important data received in overwhelming quantities.

In any military or civilian situation where the volume of information and the pace of operations can rise to high levels, cognitive overload can occur. Finding solutions to the problem of overloading cognitive processes in operators of control systems, whether artificial (in the case of training or planning simulations) or real (in the case of command and control systems) is of critical importance. Fortunately, the challenges of information overload are manifest similarly if the problem occurs in a simulation or in a real-world command and control situation. This means then that if overload can be resolved for simulation systems, the same solutions can be applied to military and civilian command and control applications as well as various commercial implementations such as cockpits, air traffic control, and computer games. Because the simulation environment can be controlled, it becomes an ideal setting to conduct experimentation.

Barriers and Issues

Issues with Creating an Experimental Environment

For the purposes of this research, an environment that creates large volumes of data under controlled conditions is necessary to allow measurement of activities that reflects cognitive loading in participants. The experiments associated with this research are designed to allow enough freedom for the participant to function normally and make choices based on the data presented, but maintain enough control to make the collected data meaningful. A non-working prototype hypervariate display could have been evaluated using qualitative methods, but the researcher chose to obtain data regarding actual usage and the actual influence of a display by using a working model inside a simulation. The simulation environment served well as an experimental platform because it offered several advantages over other alternatives:

1. The simulation system offered an accessible developmental environment where the source code was available and experienced software engineers were available to develop a prototype hypervariate display. The development environment of most command and control systems is highly restricted and frequently classified so it is therefore much less accessible for modifications.
2. The simulation environment itself offered the researcher a controlled environment where data flow rates, significant events, and operator tasking were tightly regulated. At the same time, that same simulated environment offered the operator the freedom to act as necessary based on the information received.

The advantage of studying the problem from inside a simulation system was that the data types and data delivery methods were held static (i.e., controlled variables) so that the issue of handling large volumes of information could be studied in isolation. Military

simulation systems provide such an environment, where a scenario can be created to regulate the volume of data flowing to the participant by controlling the timing of key events. With specified tasks, participants were required to act in a particular manner based on the information that was provided to them and the events as they occurred, but had the freedom to perform the required actions in the manner of their choosing.

The issue of finding an adequate experimental environment for this research led to the creation of a prototype hypervariate display using the Marine Air-Ground Task Force (MAGTF) Tactical Warfare Simulation (MTWS) system. MTWS is a computer-assisted warfare gaming system designed to support training of U.S. Marine Corps commanders and their staffs. The MTWS system is primarily used by the military in command post exercises where combat forces, supporting arms, and results of combat are modeled by the system to provide a combat realistic command and control environment without the expense or risk of using real forces. The user interface for MTWS consists of a series of windows that provide station control (e.g. connection to the game), exercise status, simulation feedback, command entry, report generation, overlay creation for map displays, and situational awareness (see Figure 1). With modification, additional windows provided a hypervariate rendering of the unfolding situation that was monitored and measured during execution.

Issues with Measurement of Cognitive Activity

A significant challenge to the execution of this research was how to find effective methods of measuring cognitive activity in study participants. Previous investigations into the effects of cognitive load on operators have varied in their methods for determining indicators of cognitive activity.

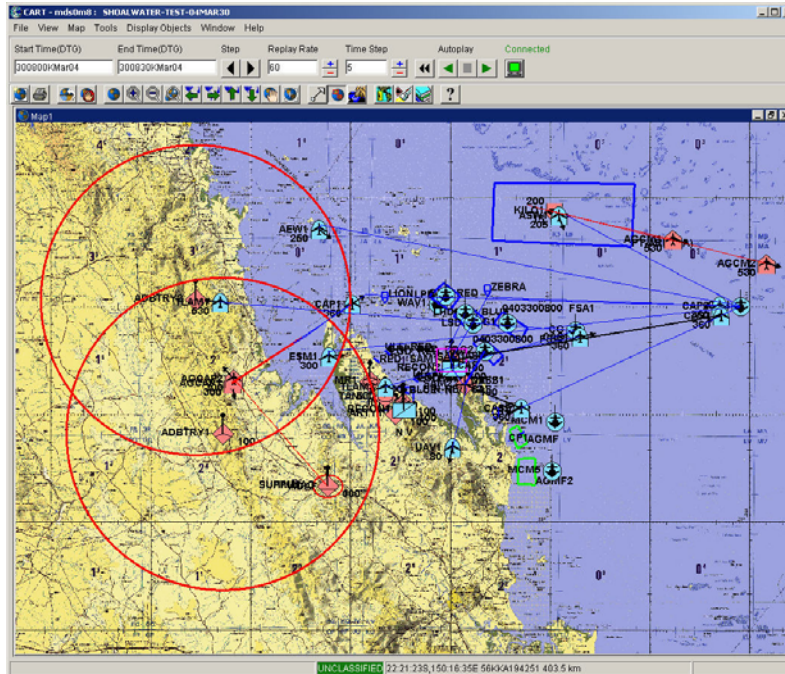


Figure 1. The MTWS user interface provides situational awareness and access to commands.

The types of data collected to measure the load placed on the operators varied widely from author to author as well, ranging from purely subjective data collection through questionnaires to highly empirical methods such as the measurement of eye and hand movement. For instance, in their investigation into cognitive load experienced in medical chat rooms, Thirunarayanan, Ryan, and Perez-Prado (2002) made subjective determinations of the load placed on their study participants by collecting data from questionnaires. Their data collection focused on feelings of confusion on the part of the participants. Walenstein (2003), in his study of levels of cognitive support afforded by the tools in Visual Café¹ for software engineers, used videotape to record the engineer's activities. He then used a review of the tape to draw subjective analysis from their actions. His interest focused primarily around the frequency of actions taken and verbal comments made by the engineers. His approach is similar to that used by others who have

¹ Visual Café is a trademark of Webgain Inc. Morgan Hill, California

performed analysis on cognitive activities in software engineering in previous studies (Robillard, et al., 1998).

Hornof and Halverson (2003) took a more empirical approach in their analysis of the influence of computer displays on users by measuring eye movements as a reflection of the cognitive strategies used by the user. Aschwanden and Stelaovsky (2002) also used eye movement, but expanded their data collection to include body temperature, galvanic skin response, and heart rate in their measurement of cognitive load on users to evaluate their data recording and analysis software.

This study used a combination of data collection techniques, including observation and measurement of task accomplishment and perceptual awareness and qualitative data collection through questionnaires. Specific data elements that were collected to reflect the level of cognitive load placed on the study subjects were:

- Operator observation of key events
- Number of mouse clicks to accomplish a task
- Time to accomplish tasks
- Number of tasks successfully completed in allotted time
- Number of missed events
- Quantity of incorrectly performed elements of a task
- Level of satisfaction

Hypothesis and Research Questions

This research examined the effects of applying hypervariate display techniques to improve system operator's cognitive awareness. The hypothesis (H) of this research was that the integration of hypervariate display techniques will significantly improve the

performance of test subjects on specified tasks, substantially improve the operator's spatial awareness, and significantly improve operator effectiveness over the use of current display systems. The null hypothesis (H_0) is that spatial awareness will not significantly improve, reaction times will not be substantially reduced, and performance will not significantly improve in test subjects that are using a display employing hypervariate display techniques. The research questions that are addressed in this research are:

1. What are the differences in awareness levels of operators when using a hypervariate display as opposed to using a standard display?
2. Does a computer operator become more efficient when using a hypervariate display?
3. How does a hypervariate display affect a computer operator's ability to accomplish assigned tasks?

Limitations and Delimitations

This research was limited in its ability to directly measure cognitive activities. While previous research and existing literature describes the process of cognition in detail, little is written about making actual measurements of cognitive levels or determining when "cognitive overload" occurs. Consequently, rather than attempting to define "cognitive overload" or measuring degrees of overload, this research focused on measuring indicators of cognitive loading such as loss of spatial awareness (Krish, 2000 and Oostendorp, 2003), reduction of reaction time (Waddington, 1996), and reduced performance in the accomplishment of desired tasks (Hinman, 1996 and Oostendorp, 2003).

As previously noted, a non-working prototype hypervariate display could be evaluated using subjective methods; however an evaluation of the effectiveness of a display should be measured empirically in order to draw acceptable conclusions. A working model was developed to do empirical measurements, however schedule and budgetary restrictions placed limitations on the scope of the model. For those reasons this research was delimited in scope in both breadth and depth.

Limitations in Breadth

As discussed earlier, hypervariate displays could apply to a wide variety of systems that require visual presentation of large amounts of information; but attempting to create prototype displays for a variety of systems for this research would have proven both costly and time-consuming and created a very large data set for analyzing results. In order to control the breadth of this research, a single simulation (e. g. a war game) system was used to demonstrate hypervariate concepts in a prototype. The selection of the MTWS system as a subject for creation of a hypervariate display was advantageous because the source code for the Graphical User Interface (GUI) was available for modification, and software engineers with experience with this GUI were accessible to make the necessary modifications. Titan Corporation (now Titan-L3 Corporation) agreed to fund the development of the prototype under the stipulation that the source code would belong to Titan and the prototype could be freely applied to the MTWS program upon completion. The funding was provided and coding was completed by Titan engineers by September 2006.

Limitations in Depth

The scope of this research was constrained in depth to provide hypervariate representation for only those activities involving ground objects in a war game simulation. Although a full hypervariate display for a simulation would include all objects in the environment (i.e., ground, air, anti-air, sea, submarine, and anti-submarine units, structures, geographical features, weather, etc.), the hypervariate prototype was constrained to ground maneuver and battles, air-to-ground attacks, and fire support between ground units.

While the depth of the display was limited, the amount of activity generated for the planned factors like ground, air-to-ground, and fire support proved to be more than adequate to over-stimulate a system operator. A single one-half hour scenario execution involved over 500 events including maneuver reports, battle results, attack events, and detection reports. Each report to the operator includes a notification of an event, the exercise time of the occurrence, and if pertinent, the location of the event. These reports were used by the system to keep the operator informed of the progress of activities as the simulation moved through time.

Definition of Terms and Acronyms

The following is a list of key terms and acronyms used in the fields of cognition, military command and control operations, and simulation. These terms are used throughout this research to demonstrate or develop concepts important to the field. The definitions provided below represent commonly accepted usage of the terms.

Air-to-Ground: An attack initiated by aircraft against forces on the ground (U.S. Marine Corps, 2001).

Augmented Cognition: The extension a user's cognitive abilities using computer technology to remove bottlenecks, limitations, and biases (Schmorrow, 2007).

Augmented Reality (AR): A merging of real and virtual objects into a single field of view (Macchiarella, 2004).

Cognition: The process of gaining knowledge or understanding (Krish, 2005).

Constructive Simulation: A simulation system in which human interaction influences the execution of the activities inside the simulation (DMSO, 2003).

Fire Support: The employment of artillery or air delivered ordnance to support military ground operations (U.S. Marine Corps, 2001).

Heads-Up Display: The projection of information into the human's field of view (most commonly a pilot) to reduce the need to change the field of view from one data source to another (Popa, 1999).

Hypervariate Display: The rendering of three or more variable factors in a display (Spence, 2001).

Graphical User Interface (GUI): A graphics-based user interface that includes user configurable windows, iconic representation of objects, and menu selection for program options (Ware, 2000).

Marine Air-Ground Task Force (MAGTF): A combination of ground, air, and logistic units organized under a single command structure intended to accomplish a designated mission (U.S. Marine Corps, 2001).

MAGTF Tactical Warfare Simulation (MTWS): A constructive simulation system used by the United States Marine Corps and the United Kingdom's Permanent Joint Headquarters as their primary war gaming system for train command level staffs in planning and execution of assigned missions (Garrabrants, 1998).

Multivariate Display: The rendering of multiple (usually two or three) variable factors in a display (Spence, 2001).

Tactical Decision Making Under Stress (TADMUS): A U.S. Navy initiative involving the combination of training techniques and decision support software intended to improve decision-making under challenging conditions (Morrison, Kelley, Moore & Hutchins, 1996).

Virtual Reality (VR): An artificial environment experienced through stimuli provided by a computer in which a user's actions partially or completely determine what occurs in the environment (Sherman & Craig, 2003).

Summary

With the rapid increase of digital data delivery occurring in all aspects of our lives, there is a need to discover more effective methods for presenting the data so that it can be processed by a computer operator more effectively. Situations in high stress conditions, particularly intense military situations where human lives could be at stake, emphasize the need for more effective data handling and processing abilities. The objective of this research was to seek ways to reduce the cognitive load of individuals faced with the onslaught of large quantities of data. The results of the research support the application of the proposed hypervariate display techniques in a variety of data retrieval systems that tend to flood a user with data.

Chapter 2

Review of the Literature

Introduction

The following paragraphs comprise a review of literature that pertains to data display techniques and the application of those techniques to cognitive processing. This review will examine previous research in cognition relevant to computer display, identify key conclusions from previous research which are relevant to cognitive processing, and describe the benefits that can be derived from improved information display efficiency. Further, this research introduces the application of hypervariate display techniques to increase the amount of information provided to a system operator while reducing the time required for understanding it and acting appropriately to the information.

Historical Overview of the Theory and Research Literature

Much of the previous research in data visualization has focused on single aspects of visualization and data processing including the topics such as filtering, search techniques, screen space management, etc. Only limited research has been performed in the combination of multiple aspects or variables into a multivariate visualization to resolve information overload problems. Three notable exceptions were found in the literature: the design and development of heads-up displays in aircraft (Popa, 1999), the advent of augmented reality devices (Macchiarella, 2004), and development and refinement of military command and control systems (Morrison, Kelley, Moore, & Hutchins, 1996).

Heads-up Display

From the development of the first graphical user interfaces, system designers have faced the challenge of presenting useful data to a user in a manner in which the user can effectively take appropriate action. This became particularly true as interface environments evolved from slow-paced overnight batch processing into a sophisticated, dynamic setting such as the cockpit of fighter aircraft where large amounts of data related to threats, navigation, and ordnance delivery are made available to a pilot and responses to the information must be made quickly and accurately.

The volume of instrumentation, navigation, and weapons delivery information encouraged pioneering efforts in the presentation of a variety of information in a way that could be assimilated quickly. Out of this research came the concept of a Heads-Up Display (HUD), where key information is projected into the field of view of the system operator to reduce the amount of head and eye movement necessary to accumulate decision-making information (Proctor, 1997). Pioneered in the 1960's, the HUD allows the pilot to monitor activity that is occurring outside the aircraft while simultaneously monitoring the internal status of the aircraft (Popa, 1999). HUDs typically have three characteristics:

- Information is projected into the person's field of view and follows head movement
- The information display is typically transparent and overlaid over the user's natural environment

- The display is projected with its focus at infinity to eliminate the need for the users to refocus their eyes when turning attention from instrument to the natural environment (Popa, 1999).

The technological lessons learned from the military experience quickly transitioned to the commercial airline industry. As early as 1989, Alaska Airlines had installed HUDs in their cockpits to improve safety and extend the ability to operate in reduced visibility conditions (Hughes, 2005). HUD technology is now being applied to the automotive industry and to the battlefield where the individual soldier will have important information available through wearable devices when required (Mansfield, 2008; Newhall, 2005). The key to a successful HUD is to ensure that the pilot is not provided with unnecessary information – Proctor (1977) noted his intentions for HUDs, “The screens can provide a lot of information. The aim is to just provide critical information.” (p. 53)

Augmented Reality

From the research of HUDs came the concept of augmenting a user’s view of reality, where objects from a virtual world are added into a view of reality (normally using head-mounted devices to project the virtual objects into the user’s field of view). Augmented Reality (AR) can be characterized as either optical based or video based formats. Video based AR uses video cameras to project a view of the real world to the user (Macchiarella, 2004). An example of video based AR is manifested in the current production of Gulfstream aircraft. The newer production aircraft include a Kollsman enhanced video vision sensor which extends the natural vision of the pilot so terrain can be seen in reduced visibility conditions such as night, fog, etc. and “blind spots” can be

eliminated (Hughes, 2005). In this sense, AR becomes a variation of the Virtual Reality (VR) world, where everything in a scene that is presented to a user is artificial (Azuma, et al., 2001).

Optical based AR employs HUD technology to project a virtual image of relevant information onto a clear screen that is positioned in the user's field of view. As with HUDs, the concept behind AR is to place information that is critical to the decision/training process directly in the operator's field of view to add to the user's understanding of the environment (Macchiarella, 2004). AR's success in extending a user's understanding of the environment is that the AR device makes supplemental information available without interfering with normal activities.

Ongoing research in AR techniques continues in the fields of medicine, construction, maintenance, and battlefield data exchange (Macchiarella, 2004). The byproduct of this research will continue to contribute to the body of developing understanding of what can and should be presented to maximize knowledge absorption without inundating the user's senses.

Decision Making Under Stress

Recognition of the challenges of assembling data into a coherent picture of unfolding events in military situations became apparent on 3 July 1988 when the USS Vincennes (CG49) fired two anti-aircraft missiles at a commercial airliner just departing from an Iranian airport. At the time, the commander of the USS Vincennes mistakenly believed that his ship was under attack from an Iranian F-14. The tragic loss of 290 persons on the Iranian Airbus 300 airliner was, as described in numerous studies, the result of the inability of the commander and his staff to sort out the massive quantities of information

being fed to them regarding both surface and air threats presented in the Persian Gulf. The commander, faced with making a rapid decision with an overwhelming amount of data to sift through, overlooked the signal that the airliner was transmitting that would have identified it as civilian with no hostile intent (Evans, 2002).

The U.S. Navy, in response to the USS Vincennes tragedy began a study of methods for improving the process of decision-making in combat conditions. A series of research initiatives were begun in 1990 under a program referred to as Tactical Decision Making Under Stress (TADMUS). The results of the TADMUS initiative focused on two areas that needed improvement: the first was to define and implement a more comprehensive and directed decision making training program. The second area of focus for TADMUS was directed at computer-based decision support; the existing command and control systems of the time provided informational displays only and did not support decision-making under stressful conditions (Morrison, et al, 1996).

Motivated by the results of the TADMUS studies, particularly the second finding related to command and control systems, Navy research laboratories designed a prototype DSS based on seven principles. Five of the principles apply directly to improving cognitive processing:

1. Data should be processed to support important tasks,
2. Presented data should make additional, supporting details available,
3. Data should be presented in a format that parallels the cognitive processes of the operator,
4. User required responses should be prompted,
5. Geographical information and system alerts should be better correlated.

The remaining two principles related directly to decision-making (i.e., evaluation of hypotheses and comparison of hypotheses) which is not relevant to this research (Hutchins, Kelly & Morrison, 1996; U.S. Navy, 2008).

Augmented Cognition

In conjunction with Navy initiatives with TADMUS, the Defense Advanced Research Project Agency (DARPA) began research in the field of Augmented Cognition in 2001. Augmented Cognition research is directed at extending a user's abilities using computer technology, removing bottlenecks, limitations, and biases (St. John, Kobus, and Morrison, 2003). The stated goal of Augmented Cognition involves the application of a number of scientific disciplines, including neuroscience, biophysiology, human factors, and computer science to identify cognitive problems in real time, and adapt user interfaces to reduce cognitive loading and improve performance (Schmorrow, 2007).

A basic Augmented Cognition system would include four primary components. First, sensors would be used to continually monitor the contextual state of the user. The collected data would be sent to the second component, an inference engine that would evaluate the user's cognitive state. The third component is an adaptive interface that adapts to the developing situation, adjusting parameters in order to reduce cognitive loading. The final component is an underlying computer-based architecture that allows the integration all other components (Schmorrow, 2008). While collection of sensory information is relatively straightforward, the analysis of the sensory data into an assessment and prediction of a user's cognitive state is challenging and is the subject of on-going research. Under Augmented Cognition research, cognitive state is being measured by means of monitors of blood oxygenation, electro-encephalogram (EEG)

readings, heart rate, and several physiological indicators including posture, pupil dilation, movement, screen activity, and mouse clicks (St. John, Kobus, and Morrison, 2003).

The Theory and Research Literature Specific to the Topic

Information Display Efficiencies

Under certain circumstances, visually presenting multiple aspects of information simultaneously can increase comprehension and speed up understanding of the information's context. An excellent example of large amounts of data displayed efficiently is Minard's map of Napoleon's march into the Russian winter during the War of 1812 (see Figure 2) (Corbit, 2008). In a single graphic, the diminishing size of Napoleon's army over time, its direction of travel, geographic location, and the corresponding temperatures are displayed for analysis. The bundling of that information is considered a classic in graphical representation. The technique of displaying multiple aspects of a set of data is referred to as multivariate display (Ware, 2000). Minard's

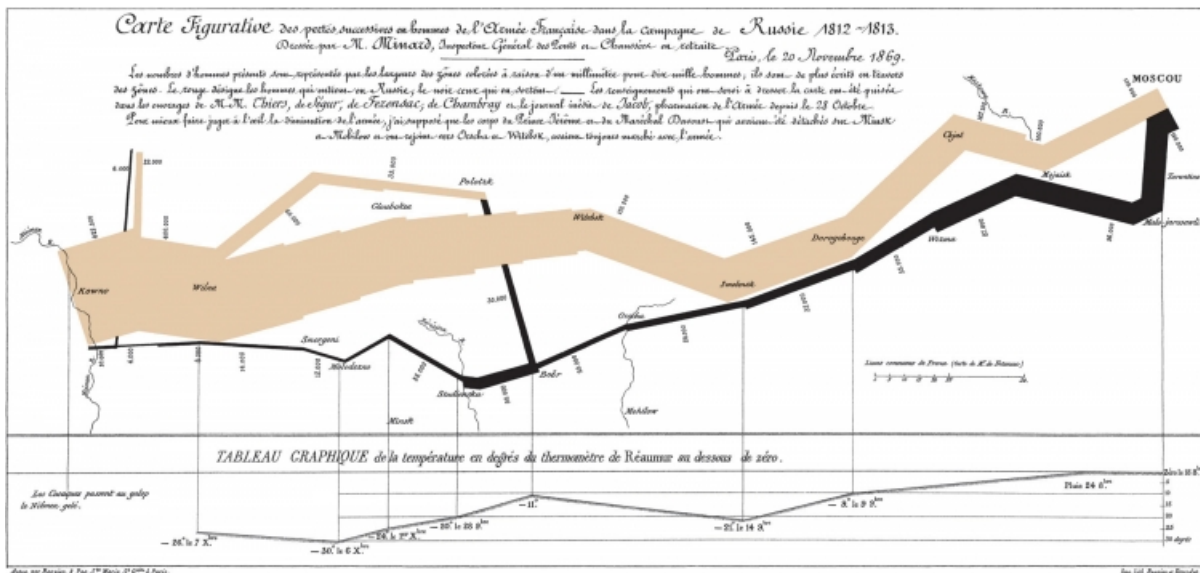


Figure 2. Minard's Map of Napoleon's 1812 Campaign (Corbit, 2008).

classic cartographic display sets the standard for concise multivariate rendering of critical decision-making information.

Preattentive Processing

An essential part of making a multivariate display effective (i.e., providing necessary information but not overwhelming the user with too much data) is to ensure that the brain can process the visualization rapidly. The application of “preattentive” features to a display can aid significantly in avoiding overload situations. Preattentive processing refers to the brain’s automatic organization of data within a visual field as a cognitive process that is automatic, fast, and accurate. Preattentive vision refers to cognitive actions that are performed before a user’s attention is consciously focused on any particular part of the interface (Healey, Booth, & Enns, 1996). It is an immediate subconscious ordering of visually presented data. Visual features that can be preattentively processed are broadly categorized as form, color, motion, and spatial position (Ware, 2000).

Healey, Booth, and Enns (1995, 1996) performed fundamental research into preattentive attention and its effect on rapid visual processing. Their findings held that the potential for preattentive processing in the display of large quantities of data is immense; they point out “Such tools, if properly designed, should allow users to perform certain types of visual analysis very rapidly and accurately.” (Healey, Booth, & Ennis, 1996, p. 106) Several preattentive factors are present in Minard’s graphic, particularly in the use of size to allow the observer to perceive the horrific reduction of Napoleon’s forces over time and spatial positioning to create the association of lower temperatures to his increased losses.

Visualization Strategies

Studies performed over a six year period lead Bhavnani (2000) to derive three generalized strategies for visualization that are applicable to the reduction of cognitive load. Bhavnani's strategies were derived from recorded observations of real-world users, cognitive analysis of the users' interactions with complex computer applications, and analysis of functionality provided by intricate applications in a wide variety of settings. His conclusions from the observations and analysis disclosed that some strategies were more efficient than others in performing complicated tasks. Among other conclusions, Bhavnani derived three visualization strategies that consistently contributed to exploit the computer's ability to display data effectively. Bhavnani's visualization strategies are:

1. View relevant information; do not view irrelevant information. The interface must allow selective display of relevant detail, filtering of irrelevant information, and selective magnification of specified details to achieve this particular requirement.
2. View parts of distant information to fit simultaneously on the screen. Related to limited screen space, this ability requires a view that allows comparison of various parts of the data space simultaneously.
3. Navigate and select in global views, manipulate in local views. This requires both global and local views that are available and correspond to each other (Bhavnani, 2000).

Filtering

Bhavnani's first visualization strategy can be dealt with using filtering techniques to bring only relevant information to the user. Considerable research has been conducted in the area of filtering in circumstances where overload can occur, particularly with the

advent of the worldwide web and other Internet based services where users are literally flooded with data. Berghel (1997) and Heo and Hirtle (2001) focused their research on managing the large volumes of feedback from Internet search results through intelligent filters (i.e., intelligent agents). Ho and Tang (2001) concentrated their research on filtering techniques as well; suggesting information can most effectively be controlled through control of the quantity of information provided, but not without potential consequences. While their research showed the benefits of filtering as an essential part of managing cognitive load, they found that it was not the complete solution. Filtering is not perfect, and as a consequence, key information may be inadvertently withheld from the user (Ho & Tang, 2001). The user is the best person to determine what data is relevant and what is not necessary, so an effective display will allow operators to customize the filtering of information to their individual requirements.

Multivariate Display

While filtering cannot be the complete solution for managing cognitive load, filtering in conjunction with visualization techniques may come closer to a complete solution as suggested by Bhavnani (2000). By combining Bhavnani's last two visualization strategies into a display that allows both a global view and local control, it becomes possible to provide visibility into multiple variables simultaneously. Multivariate displays that feature preattentive aspects are already in use in military command and control systems and military war games to a limited degree, today. The display that is used in most current military simulation and command and control systems employ visualization techniques that take advantage of several preattentive features and include a detailed symbology set (like those represented in Figures 1 and 3) that provides a variety of key



Figure 3. A sample command and control display with unit symbol.

information about the objects they represent. Four examples of these systems that are currently in use are the Global Command and Control System (GCCS), the Command and Control Personal Computer (C2PC), the Marine Air-Ground Task Force (MAGTF) Tactical Warfare Simulation (MTWS), and the Joint Conflict and Tactical Simulation (JCATS) system.

Both GCCS and C2PC are command and control systems employed to support military commanders at various levels of command to plan and control actual operations. GCCS has variants for each of the four major United States military services that came into operation in 1996 (Department of Defense, 1996) and remain in use today. C2PC is a Windows-based application intended to support military decision-making at the tactical level (U.S. Marine Corps, 2002). Both GCCS and C2PC are primarily geospatially oriented; the primary method for conveying information is through a map display similar to the display shown in Figure 3.

Like GCCS and C2PC, military simulation depends on a map display to convey important decision-making information to their users. Both MTWS and JCATS employ

this method as well. MTWS provides military simulation (i.e., wargaming) at a level that permits easy control of larger groupings of objects (referred to as units) (Garrabrants, 1998). JCATS is an entity-level simulation, meaning simulation objects are controlled and displayed individually (e.g. individual troops or tanks are controlled rather than groups of troops or tanks). JCATS objects are directed from commands issued from the map display (U.S. Air Force, 2005).

Figure 3 (an extract of a military command and control display), color, form, and spatial position are used to preattentively depict the allegiance, unit type, and geographic location of each object. Red, diamond shaped objects represent hostility while blue, rectangular shaped objects represents friendly disposition. The objects with circles inside of the symbol represent tank objects and the crossed lines (“X” shapes) depict infantry objects. Finally, the positioning of the object on the map provides the observer with an accurate geographic positioning of the objects that the symbol represents and its position relative to other objects. With these preattentive features, an operator gains an understanding of the general situation before any conscious thought regarding that situation occurs.

The preattentive features of the symbols in Figure 3 are combined with other display notation that gives the observer an “at a glance” view of additional information important to the management of those objects. While this additional information is not preattentively processed, it makes key information readily available to the user for decision-making. For instance, the symbol labeled “MARCO1” in Figure 3 has a notation at the top of the symbol to indicate the size of the unit, and notations on the sides to show the unit name, its relative strength, and in what direction it is traveling.

The variables provided by the representations in Figure 3 fulfill Bhavnani's first visualization strategy for the operator by providing a multivariate visualization that permits the operator to view a variety of highly relevant information specific to that object. Object characteristics that the display in Figure 3 provides are:

- Allegiance (e.g. blue for friendly, red for hostile)
- Size (e.g. three dots for platoon, a single bar for company size)
- Unit type (e.g. the circle or crossed lines inside the symbol)
- Location relative to a map

The icons are rich in data presentation, however, the display in Figure 3 falls short of fulfilling Bhavnani's second and third strategies in that it provides a local view but does not relate the local view to a global situation and it does not provide an effective means of seeing distant information that is relevant to the object. Because the display in Figure 3 (and most command and control systems) are map based, the display can either provide a detailed, close-in view of a condition that restricts the number of objects that can be seen or manipulated, or the display can provide a wider view that provides an overview but loses significant detail. The geographic view is very effective at displaying spatial relationships among objects, but the map's necessity for scalar integrity prevents global and local views from being shown simultaneously in an effective manner. That same scalar integrity also interferes with efficient viewing of events that are separated by wide distances. This is the same type of multivariate display used by MTWS for unit identification; consequently the MTWS system shares many visual similarities with command and control devices.

presentation to a system user that provides all three aspects of Bhavnani's display strategies. Hence, the proposed hypervariate display combines the multivariate characteristics of the symbology described above with additional visibility to provide for an ability to make rapid comparisons of disparate objects, and allow for local viewing of objects that are geographically widely separated in a real-time environment. The conceptual display takes advantage of filtering, multivariate object rendering, and additional preattentive characteristics.

Contribution of This Study to the Field

This study expands the existing body of knowledge regarding visual presentation of large amounts of data where complex ideas must be offered in a readily understandable manner. This investigation will empirically determine the benefits of combining the concepts behind augmented reality and heads-up displays (i.e., presentation of key data elements in the field of vision) with the supporting research behind Tactical Decision Making Under Stress (TADMUS) and Augmented Cognition (i.e., principles of large volume data presentation and understanding the cognitive state of the user). This research contributes to several key issues in the field of data presentation: the application of preattentive factors in combination, the employment of the principle of geospatial independence, and the use of user controls in a visual display for the purposes of reducing the cognitive load on computer users. The results of this research will also suggest future directions for ongoing research in command and control devices and interfaces and could offer direction for the adaptive interface research being conducted under Augmented Cognition.

Summary

Considerable research is available regarding visualization techniques in general and large amounts of research can be found that addresses specific visualization problems. However, current research primarily focuses on the form and functions of a user interface as a discrete issue, and only a small portion of the literature combines these techniques to increase the effectiveness of the decision-making process.

Visualization researchers have begun to address the issue, particularly in the military environment where Heads-Up Displays (HUDs) were pioneered. In evolutionary progress, additional visualization techniques beyond HUDs have been developed, including Augmented Reality, and Augmented Cognition. The tragedy of real-world events lead the military to critically look at data presentation to commanders under the pressure of battle. The resultant research, referred to as Tactical Decision-Making Under Stress (TADMUS), has lead to a variety of initiatives to design command and control systems more effectively for commanders by using a combination of visualization techniques to focus attention to critical information. While the research may have started in the military world, the concept of improving understandability and interpretability of large amounts of fast-moving data has found application in civilian and commercial environments such as computer gaming, aircraft instrumentation, and emergency response coordination devices.

The research would indicate that a combination of factors, specifically the use of preattentive features, specific visualization strategies, and filtering can create a hypervariate visualization environment that enhances decision-making and improves a user's comprehension of developing situations. This dissertation addresses the application

of these hypervariate techniques to a new user interface to determine if the cognitive load placed on the user can be reduced.

This research contributes to the expanding breadth of knowledge in the area of cognition and human-computer interaction by offering empirical data that verifies fundamental concepts for display efficiency that should be applied to future graphical user interfaces. The application of hypervariate display techniques offers a potential solution to the challenging problems of information overload; the potential benefits justify further investigation and research.

Chapter 3

Methodology

Research Methods Employed

An experiment was conducted with two conditions to determine if the application of hypervariate principles to a user interface significantly improved cognitive processing. The conditions that were compared were two formulations of a user interface (i.e., without hypervariate enhancements and with enhancements) to an unclassified military simulation system. If application of these principles improves operator processing speed and user comprehension, the principles could have broad application across a variety of systems that convey large amounts of data to a user.

Experiment Design

The experiment consisted of a single independent variable with three dependent variables. The independent variable was represented by the type of interface to be used. There were two factors: the original, standard user interface, and the prototype hypervariate interface. The dependent variables were workload (measured in time required to complete tasks), comprehension (measured by the number of missed events and requests for data), and efficiency (measured in the number of steps required to complete a task). The hypothesis (H) of this research was: integration of hypervariate display techniques will significantly improve the performance of test subjects on specified tasks, substantially improve the operator's spatial awareness, and significantly

improve operator effectiveness over the use of current display systems. The null hypothesis (H_0) is that spatial awareness will not significantly improve, reaction times will not be substantially reduced, and performance will not significantly improve in test subjects that are using a display employing hypervariate display techniques; *alpha* (α) is set at .05.

The advantage of studying the problem from inside a simulation system was that the data types and data delivery methods could be held static (i.e., controlled variables) so that the issue of handling large volumes of information could be studied in isolation. In order to ensure that other variables did not influence nor have an effect on the dependent variables, additional potential variables in the experiment, such as hardware configuration, window arrangement (on the screen), the simulation setup, and the simulation scenario were held constant during the experiment. Hardware was tightly controlled by performing all experimental runs with identical hardware configurations. Identification of the hardware types is provided in the Apparatus section below. For each trial run, the window configuration on the screen was set up to a default configuration. Test subjects were free to reconfigure window layout for personal preferences once the experiment had begun, but every subject began the experiment with identical screen configurations. A controlled simulation setup meant that the beginning of each run of the experiment started in the same situation for all objects represented in the simulation. One of the strengths of using simulation software in a controlled experiment is that it can save the state of the simulation at any time during execution and restore to that state with exactly the same unit locations, disposition, and assigned orders at any point in the scenario. With the situation saved in the simulation at the start of the scenario, it was a

simple matter to restart the simulation at the same identical place. The beginning situation, the assigned missions, and the tasked responsibilities are described in Appendix A.

The final controlled variable was the execution of the simulation scenario. In order to control the scenario, it is necessary to run the simulation at the same rate for all trials, execute the same events at the same frequency and run the simulation for the same period of time. Again, the strength of using this type of simulation is that planned events are easily scheduled to a pre-planned event time so that they will always occur at the same time in each simulation run. Similarly, the rate at which the simulation advances time and length time of simulation periods are easily controlled by the simulation controller. The modifications to the Marine Air-Ground Task Force (MAGTF) Tactical Warfare Simulation (MTWS) interface created two environments (i.e., the original interface and the prototype hypervariate display) so that operator actions and time required to accomplish assigned tasks could be measured, recorded, and compared in each environment.

Population

Participants for this study were a selected judgmental sample from a limited population of volunteer personnel with experience in the use of the MTWS system. The choice of using this particular segment of the general population rather than selecting a totally random sample was because:

1. The complexity of the MTWS system generally necessitates an introductory training period of four weeks for new personnel. A training requirement of this length makes the use of study participants that are unfamiliar with the MTWS

system prohibitive. The cost to train new study participants would be too expensive both in terms of time and effort.

2. The personnel that are trained on MTWS have military background, so they are familiar with terminology, techniques, and procedures that will be useful during the execution of the study.

The disadvantage of using a judgmental sample is that errors are not measurable (Dubois, 1979). This disadvantage was mitigated for this research by performing the selection of the population by an expert in the field thereby reducing the size of potential errors (Dubois, 1979). While selection of a judgmental sample was less desirable than a totally random sample, the circumstances described above dictated a reasoned approach to sampling. The selected sample closely resembled the general simulation population in that both the sample and the general population had general military experience, had used computer managed command and control systems previously, were age distributed similarly, and had a wide distribution of computer experience. By ensuring that the sample was drawn from a variety of MTWS experienced operators, the potential for sampling errors was reduced.

A total of 18 volunteers participated in the research to provide a valid comparative model in analyzing the collected data. The study participants were selected from four MTWS sites throughout the U.S. (Naval Amphibious Base Coronado, CA, Camp Pendleton, CA, Marine Air-Ground Combat Center, 29 Palms CA, and Quantico Marine Base, VA). The actual data collection occurred at three locations in California during October and November 2006. Demographic cross-sections of the study participants included individuals with all levels of education (e.g. high school through post-graduate

degree) and technical (e.g. novice to highly experienced) and military experience (measured in years of service). The age of the participants ranged from 18 to 60 years old, with the average falling in the range of 31-35 years. All of the participants but one were male (reflective of the general combat and military simulation populations).

Apparatus

In order to ensure that every participant experienced the same presentation and scenario, the same hardware was used throughout the study. The use of the same hardware ensured that undesired variances in the experiment were not introduced by variations in screen resolution, hardware configuration, or system performance. The servers that provided the simulation engine were Dell Inspiron 700m computers running the Linux operating system and the MTWS core software. The users did not see nor directly interact with the servers; they provided the researcher monitoring the experiment with the means to start, stop, and restart the simulation at the beginning of the scenario. The test subjects performed their assigned tasks at one of four Dell Inspiron model 9100s running the Windows XP operating system and the MTWS user interface software. The user workstations were selected because of their excellent portability combined with a very high resolution screen (15.4 inch 1920x1200 pixels). For consistency's sake, all user workstations were equipped with the same brand/model of mouse. During each iteration of the experiment, the system was configured so that all windows were arranged and sized in the same way to eliminate variances that would skew the study's results. In this way, the hardware, and the screen configuration of the user interface variables were controlled during the experiment.

Data Collection

As described earlier in this Chapter, data was collected to determine the effect of the prototype hypervariate display relative to three dependent variables: workload, comprehension, and efficiency. Workload was measured in terms of time required to accomplish assigned and implied tasks as well as the number of late or missing tasks. Comprehension was reflected in recording the number of events that should be observed in comparison to the number that were missed. Finally, efficiency was measured in terms of the time and steps required to accomplish assigned tasks.

Data was collected during the experiment using TechSmith's Morae² software. Morae records and synchronizes both video and data, creating a digital record of system activity and user interaction. The recorded data includes video recording of all screen activity, camera video and audio of the operator's actions, facial expressions, and comments, mouse activity, keystroke activity, window and dialogue events, and screen text. The analytical segment of the Morae software permits searching for specific events in the synchronized recordings, and provides time-based metrics for time on task, number of mouse clicks and page activities, time spent in a particular window, delay times, and other productivity measures. Each of these metrics has associated graphing capabilities as well.

Analysis of the data collected by Morae provided quantitative data to measure the dependent variables. While not as sophisticated as the biometric devices used to measure some of the same variables for Augmented Cognition experimentation (St. John, Kobus, & Morrison, 2003), the Morae software provided a cost-effective solution for this

² Morae is a trademark of TechSmith Corporation, Okemos, Michigan

research while supplying a wide variety of data points to perform the analysis. The operation of the Morae software did not interfere with the proper execution of the MTWS software and the prototype hypervariate display and did not have a detectable impact on system performance or responsiveness.

Following completion of the experiment, each user completed a questionnaire (see Appendix B) to collect qualitative data primarily relevant to levels of satisfaction with the functionality and practicality of the current and prototype interfaces. The questionnaire was designed to conform to Nielsen's (2005) ten usability heuristics in order to obtain a qualitative measure of usability from the participants. Ten of the questions (i.e. questions 1, 4, 5, 6, 10, 11, 12, 14, 17, and 19) collected qualitative input regarding the subject's awareness (comprehension) of unfolding events, four were related to the user's perception of workload (i.e., 2, 7, 8, and 9), and six questions (i.e., 3, 13, 15, 16, 18, and 20) collected qualitative data regarding efficiency.

The Prototype Hypervariate Display

Spence (2001) introduces the concept of a hypervariate display, expanding on the concept of a multivariate presentation where three or more attributes are presented. Spence's focus with regard to hypervariate display was primarily toward display of purely numeric data. For the purposes of this study, the term *hypervariate display* is used to describe a presentation to a system user that provides all three aspects of Bhavnani's (2000) display strategies (i.e., view relevant information, view distant information together, and view global and local information together). Hence, prototype hypervariate display used in this study combines the multivariate characteristics of the symbology described above with additional visibility to provide for an ability to make rapid

comparisons of disparate objects, and allow for local viewing of objects that are widely separated (geographically). The conceptual display takes advantage of filtering techniques, multivariate object rendering, and additional use of preattentive characteristics.

A fully functional prototype hypervariate display was designed and developed for the MTWS system as a supplemental interface to provide a means to measure the effects of hypervariate display on user cognitive processes. The prototype display consists of three interrelated windows that were added to the MTWS interface, used for configuration, global visualization, and detailed analysis.

The three windows, “Objects of Interest”, “Alert Settings”, and “Events of Interest” together create a hypervariate display that compliments rather than replaces existing interfaces. Conceptually, a user selects a subset of objects that require scrutiny from the global situational display that MTWS normally provides. A single MTWS display will typically have 50 – 100 objects that the operator is expected to manage, observe and control; the Objects of Interest (Figure 5) window will typically have ten or fewer objects (although the software does not limit the number of objects the user can add to the window) selected by the operator as the objects of most concern based on the developing situation. Objects can be added or removed at the discretion of the operator. Once these “objects of interest” are added to the window, the user can then configure the system to provide alerts when events occur that are of critical importance using the Alert Settings window. Finally, the operator will be able to pull selective information relative to the object to perform detailed analysis of events in the Events of Interest window.

Object	Dir...	P...	E...	Alert
1_LAR_2 100	↙	100	100	DETECTION - VISUAL LOST
3_AT_2 99	↘	68	88	DETECTION - VISUAL LOST
F_2_2 1 S 89	↙	60	99	GROUND ENGAGEM... ASSESSMENT
E_2_2 100	↑	100	100	DETECTION - AURAL ACQUIRED
1_AT_2 1 99	→	64	50	GROUND ENGAGEM... ASSESSMENT
A_1_2 0	↘	7	83	DETECTION - VISUAL LOST
B_1_2 S 99	↑	97	100	DETECTION - VISUAL IMPROVED
C_1_2 0	↘	13	84	DETECTION - VISUAL LOST
2_AT_2 98	↘	45	81	GROUND ENGAGEM... ENGAGEMENT TERMI...
K_3_2 S 92	↑	77	96	GROUND ENGAGEM... ASSESSMENT
L_3_2 S 99	↑	96	100	DETECTION - AURAL LOST

Figure 5. The Objects of Interest window features many descriptive symbols of object status.

Figure 5 provides a view of the Objects of Interest window. The objects displayed in this window are selected by the user from anywhere on the MTWS global display as those items that require particular attention. By bringing geographically disparate objects together, attention can be focused directly on those that are of critical importance regardless of their proximate location. The display provides immediately discernable information regarding unit identity, activity, personnel and equipment status; and also provides an alert when the system identifies events that have been selected by the user as important. A single click on an object changes the focus of the system to that object (e.g.

in Figure 5, the object identified as “1_AT_2” has been selected). The user can then request detailed information about the object, center the map on the object, or configure the alert setup by selecting one of the icons in the toolbar. Alerts are provided to the operator using a color-based preattentive clue. As events that have been identified as of particular concern occur, a yellow bar on the right side of the window highlights a headline of the event; personnel and equipment status summaries are seen as “thermometer” graphics for preattentive interpretation of critical information. Commands (i.e., directive orders to the simulation objects) that can normally be issued from the standard MTWS map interface can also be issued from the Objects of Interest window. The Objects of Interest window is not bound by the same requirements for spatial integrity that a map view is – objects that are geographically separated by significant distances are seen together. Events that are deemed as significant are immediately brought to the attention of the operator through the yellow alert bar and the means of obtaining more detail regarding the object’s activities or focusing in on the object in the geographic display are at the user’s disposal.

The second window associated with the prototype hypervariate display is the “Alert Setup” window (Figure 6). This window allows the user to select the types of alert notifications desired for the Objects of Interest window (e.g. the yellow bars in Figure 5). This configuration can be set individually for each object contained in the Objects of Interest window, so alerts for one object can be different than those of another or they can be set globally to apply to all objects. The Alert Setup window contributes to the hypervariate display by allowing the user to define an interest set of those elements of

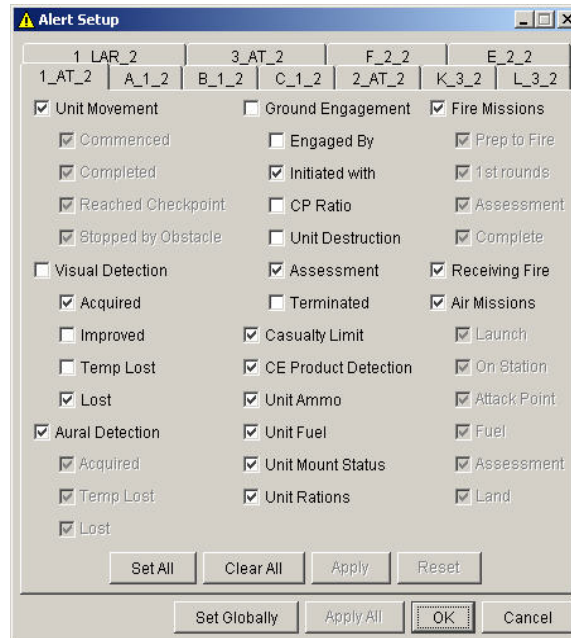


Figure 6. The Alert Setup window allows the operator to customize alert notification.

particular importance for an object in the simulation. Because each object is individually configurable, key elements that are relevant to the individual operator are highlighted.

The Events of Interest Window (Figure 7) is the third element of the prototype. This window provides a filtered, configurable view of all of the events associated with the objects contained in the Objects of Interest window.

Presented in row and column orientation (spreadsheet style), each of the columns can be used to sort the data with a simple click of the mouse. Additionally, the order of presentation of the columns can be rearranged to bring important data to a more convenient location. When a particular row (i.e., event) is selected, clicking the location button places a location marker on the map to indicate the geographic position where the event occurred (the map will be automatically centered on the mark) and the map can be instantly recentered to the location marker. The normal MTWS presentation of these events is provided in a scrolling window for all objects (not just those relevant to the

The screenshot shows a window titled 'Events of Interest' with a menu bar (File, Tools, Window) and a toolbar. The main area contains a table with the following columns: I., DTG, UTM, Category, Subcategory, Details, and LatLon. The table lists six events with various detection and engagement details.

I.	DTG	UTM	Category	Subcategory	Details	LatLon
1 *	210734Z0CT04	11SQK336051	DETECTION - AURAL	ACQUIRED	TRACK: 26 DIRECTION: NW	35:15:51N,114:25:52W
2 *	210740Z0CT04	11SQK336051	DETECTION - AURAL	ACQUIRED	TRACK: 66 DIRECTION: N	35:15:51N,114:25:52W
3 *	210801Z0CT04	11SQK336051	DETECTION - AURAL	ACQUIRED	TRACK: 66 DIRECTION: NE	35:15:51N,114:25:52W
4 *	210801Z0CT04	11SQK330056	DETECTION - VISUAL	ACQUIRED	TRACK: 157 TANK PLATOON ID: Y_2 TROOPS 1; AK-74 4; T-72 1	35:16:07N,114:26:17W
5 *	210802Z0CT04	11SQK330056	DETECTION - VISUAL	IMPROVED	TRACK: 157 TANK PLATOON ID: Y_2 TROOPS 2; AK-74 12; T-72 3	35:16:05N,114:26:16W
6 *	210803Z0CT04	11SQK336051	GROUND ENGAGEMENT	ASSESSMENT	REPORT: GROUND_ENGAGEMENT 7,11SQK336051,210803Z0CT04;AGCON_2,CONT_2; Initial engagement times: Y_2; 210756Z0CT04 A_1_2; 210756Z0CT04	35:15:51N,114:25:52W

Figure 7. The Events of Interest window displays events relative to the referenced object.

object(s)). While this standard interface provides details about all events, it is difficult to discern key events from the far more frequent mundane occurrences and it is virtually impossible to filter the information relevant to a single simulation object. Because the Objects of Interest interface performs automatic filtering of these reports (with tabs for each object in the Objects of Interest window) the interface also provides a means of observing a history of the object's activities since the start of the simulation without having to sort through thousands of event notices. Comparison of events relative to multiple objects' events is also possible in the Events of Interest window.

In the aggregate, the three windows of the prototype hypervariate display expand the standard MTWS interface to include data elements that are frequently used in operator decision making but require multiple steps to extract using the standard MTWS interface. Additional characteristics of the objects shown in the hypervariate display are:

- Personnel and equipment status
- Customized alerting on key events
- Filtered and reconfigurable histories of object events
- Rapid refocusing of attention to activities of concern

The combination of these elements meets Bhavnani's (2000) criteria for effective visualization. The hypervariate display provides a selective (i.e., filtered) view of events

that are of critical concern to the user, displaying only information that is relevant to the system operator. By combining geographically disparate objects in a single view, distant information and events are brought together for analysis. This provides the user with both a global and local view of events and object status in the simulation.

The hypervariate display, implemented as described above, provides the MTWS operator with critical decision-making information “at a glance”. The display provides more focused information in a smaller display with more efficient access to stored data. The use of the prototype should reduce the number of map manipulations, searches through event files, and queries against unit status. These reductions will result in more efficient cognitive processing, the end result being a reduction in cognitive load.

Specific Procedures Employed

Procedure

Each participant in the study was provided with an initial 30 minute training session in the use of the prototype hypervariate display. Following the training, the participant was then introduced to the scenario, and then the guidelines and responsibilities were briefed to the participants. They were then given a short period of time (e.g. 3-5 minutes) to familiarize themselves with the starting situation, orientation of the interface, and to customize layout to their personal preferences.

Participants in the study performed two 30-minute sessions, run one immediately following the other. The scenario was designed to begin simulated activity slowly and gradually increase the tempo of the activity throughout the session. The scenario was intentionally designed to reach a volume of activity (and amount of data being supplied to

the participant) during the last few minutes of the session that even a proficient operator would be challenged to effectively keep up. The simulation advancement rate was accelerated to 3:1 (i.e., three minutes of simulation activity occurs for each minute that occurs in real time) to achieve this level of activity. Accordingly, during the 30 minutes of simulation activity, 1.5 hours of simulation events had occurred.

During the execution of the scenario, the participant was given a number of specified tasks that had to be accomplished while simultaneously monitoring the status of assigned units and reporting a pre-defined set of significant events as they occurred. The scenario was designed to make accomplishment of some tasks and the reporting of significant events challenging but not impossible. Over the course of the 30 minute session, approximately 150 significant events occurred, 21 of which were of vital importance to the operator. The number of overt actions (i.e., offensive or defensive) is decided by the participant based on his or her perception of the developing situation. Six specifically assigned tasks were required of each operator during the course of each run of the experiment; employ two air missions against enemy targets (Tasks 1 and 2), utilize an artillery fire mission to engage the enemy (Task 3), employ a reconnaissance unit to discover enemy activity (Task 4), establish a defense of the main line of communications (Task 5), and conduct a direct attack on an objective (Task 6).

Upon completion of the first scenario run, a questionnaire was completed collecting subjective user satisfaction information (Appendix B). While the participant was completing the questionnaire, the second scenario was set at the beginning, and the interface was changed (if the prototype hypervariate display was used first, then the

standard interface was loaded, and if the standard interface was used first, then the hypervariate display was then loaded).

After a short break, the participant was given final instructions and the second scenario was run in the same manner as previously described. When the participant had completed the second scenario, a second questionnaire was completed to collect qualitative data regarding user satisfaction with the second interface.

The second scenario was designed to be similar to the first, using the same terrain and units, however the sequence of events and the location of the events were varied. A similar-but-different scenario design prevented bias introduced by familiarity with the scenario but simultaneously avoided wide variance in the results of the experiment. The altered scenario effectively broke any linkage to long-term memory that might remain from the previous scenario run. By running similar but different scenarios, a new variable is not being introduced to the experiment. The use of scenarios that differed significantly would create such radically different environments that comparisons between the first and second runs would be meaningless. Repeated measures analysis of variance (RM ANOVA) will be employed during data analysis to ensure that the use of the same participants to execute scenarios with both the hypervariate and the standard displays and ensure that a bias has not been introduced. In addition, the experiment was designed to be counterbalanced by having half the participants start with scenario 1 and finish with scenario 2 while the other half started with scenario 2 and finished with scenario 1.

Data regarding workload, comprehension, and efficiency were extracted from the Morae files following both runs of the scenario. This data, combined with the qualitative usability data obtained from the questionnaires, was used to evaluate the ability of the

prototype hypervariate display to improve operator efficiency and reduce cognitive loading. The qualitative data will be evaluated using t -test analysis to test the means of the two populations (experiments under the normal interface versus experiments under the hypervariate display). While the use of t -test analysis of a small sample could potentially lead to Type I errors, this concern is considered to be of minimal risk to this research.

Approach to Measuring Cognitive Activity

An assessment of the level of cognitive activity is possible by measuring and comparing human performance under controlled conditions. The collection of human performance data under stressful conditions where standard interfaces are available provides control data that can be compared to data collected under identical conditions using the prototype hypervariate display. The human performance data that was collected for this can be categorized as quantitative and qualitative. The data collected through the use of Morae software and user surveys to measure cognitive activity for this dissertation was:

Quantitative (collected with Morae)

- Time required to complete assigned tasks
- Number of actions required per task
- Number of tasks completed in allocated time
- Number of tasks performed incorrectly
- Number of missed significant events
- Number of requests for supplemental information

Qualitative/subjective (collected via user surveys)

- Perceived ability to control objects and situation
- Perceived levels of usability/efficiency
- Perceived levels of awareness

Formats for Presenting Results

The majority of the data collected during the experiments was quantitative, intentionally supplemented with qualitative data where quantitative could not be obtained or where its collection was not practical. The three research questions posed in Chapter 1 were answered using the data collected as follows:

1. What are the differences in awareness levels of operators when using a hypervariate display as opposed to using a standard display? This research question is intended to understand how comprehension changes when using a hypervariate display. Does comprehension of the developing situation improve, remain static, or get worse? Comprehension is measured by the:
 - Number of missed significant events
 - Number of requests for supplemental information
 - Perceived levels of awareness
2. Does a computer operator become more efficient when using a hypervariate display? This question addresses the changes in the speed by which users can accomplish a task, where efficiency is reflected by the:

- Time required to complete each task
 - Number of significant asks completed in allocated time
 - Perceived levels of usability/efficiency
3. How does a hypervariate display affect a computer operator's ability to accomplish assigned tasks? The final research question addresses the concern regarding how effectively a number of tasks can be completed with each interface; workload is reflected by the:
- Number of actions required per task
 - Number of tasks performed incorrectly
 - Perceived ability to control objects and the situation

Analysis of the accumulated data was performed using Minitab³ statistical analysis software to determine the significance of the collected results. The statistical analysis functions were used to calculate means, perform analysis of variances (ANOVA), and provide graphical presentation (e.g. charts and graphs) of the collected data.

Resources Used

Software

The MTWS system was used as a subject for the development of a hypervariate display. MTWS was selected as the platform on which the prototype would be developed because of its availability and flexibility for adapting a test environment to create levels of activity that would generate cognitive stress. MTWS is an unclassified computer-assisted warfare gaming system designed to support training of U.S. and U.K. military commanders and their staffs. The system is primarily used in command post exercises in which combat forces, supporting arms, and results of combat are modeled by the system.

³ Minitab is a Trademark of Minitab Inc, Pennsylvania

All aspects of the MTWS system, including its input data and final products are unclassified and therefore its use and the products created for this dissertation do not require military release or review.

Software Engineering Support

The user interface to MTWS was modified to create a prototype hypervariate display that was used for analysis of cognitive load on operators during execution of a previously established scenario. Software engineers from Titan Corporation (the original developers of the MTWS software) created the prototype using corporate internal funding and based on a design provided by the author. Developmental testing of the developed prototype was performed by the author and other Titan employees prior to its use for this evaluation.

IRB Approval

Human subjects with some experience in the use of MTWS were employed to conduct the experiment. Subjects were selected from military and government contractor personnel assigned to three of the five MTWS sites in the United States. This pool of experienced operators served as the source for the comparative analysis. Institutional Review Board (IRB) approval was obtained to perform this data collection. Appendix C is the IRB approval for this research. Adult Informed Consent Forms (sample in Appendix D) were obtained from each of the test subjects.

Reliability and Validity

The primary objective of the data collection process described above was to ensure that the collected data was valid and accurately reflects causal relationships between changes in the environment and cognitive loading. As such, the procedures outlined

above were intended to be as unchanged from scenario run to scenario run to hold potential variables constant. Each participant received identical starting instructions (Appendix A) and was provided with identically configured computers and interfaces for each session of the experiment. The speed of the simulation was strictly regulated by the system, and the duration of each session was controlled by the author to run for precisely 30 minutes each.

While the data collection methods were not as well instrumented as those used by the researchers of Augmented Cognition (biometric data gatherers), the use of Morae software to record all of the quantitative aspects of the data for collection, analysis, and detailed study ensured that the supporting data was accurate and complete. Additionally, qualitative data was collected immediately upon completion of each session of the experiment to be sure that the participant's impressions were reliably recorded while the experience was still fresh on their minds. This research builds on research conducted in Augmented Cognition (St. John, Kobus, and Morrison, 2003 and7, 2005) and Tactical Decision-Making Under Stress (TADMUS) (Hutchins, Kelly & Morrison, 1996). It is believed that this research will help create a foundation for future study of methods for presenting large amounts of data in a way to avoid cognitive overload.

Summary

The purpose of this research was to determine the effect of hypervariate display techniques on the cognitive abilities of the research subjects. This research furthers the investigations of other researchers like Bhavnani (2000) and Schmorow (2008) by combining their results into a prototype hypervariate display that explores the effect of combined factors on cognitive processing.

The detailed experimental methodology collected quantitative and qualitative data relevant to the cognitive processing abilities of the subjects (participants). Through careful selection of experiment participants, a counterbalanced approach to the experiment, and strict adherence to the procedures described in this chapter, a high degree of validity and reliability was maintained.

Chapter 4

Results

Findings

The analysis of the results of the experiment will be split into three groups in relation to the dependent variables defined in Chapter 3: workload, comprehension, and efficiency. These variables will be examined individually in order to independently consider the effects of the hypervariate display on the participants; then a comprehensive view of the results considering all three variables will be discussed.

Because the 18 participants were measured twice (once with the standard interface and once with the hypervariate display), a repeated measures analysis of variance (RM ANOVA) was performed for the quantitative data collected during the course of the experiment. Performing an RM ANOVA provides the opportunity to examine the influence of having the participant performing the experiment more than once (twice in this case).

For this concern, the hypothesis (H) is that spatial awareness did improve significantly as a result of having previous experience with the scenario. The null hypothesis (H_0) is that spatial awareness did not significantly improve as a result of a participant's previous experience with the simulation system. If the participant p values for any of the ANOVA results (within subjects) are less than the confidence level - *alpha* (α) of .05, then the null hypothesis should be rejected for that factor (i.e., that spatial awareness improved as a

result of that factor), the hypothesis is supported indicating that participants were unduly influenced for the second run of the scenario by performing the first run. Acceptance of the null hypotheses means that the influence of multiple simulation runs on other variables is insignificant and can be ignored – the repeated measures ANOVA will consider the participant as a factor only to ensure that multiple measurement of the same participant was not a factor of significance.

Six assigned tasks were required of the operator during the course of each experiment: employ two air missions (Tasks 1 and 2), utilize artillery (Task 3), employ reconnaissance (Task 4), establish a defense (Task 5), and conduct an attack (Task 6). The quantitative data collected during the various runs of the experiment are compiled in Appendix E, and qualitative data collected through the surveys administered immediately following each run of the experiment (with comments) are provided in Appendix F. All statistical analysis was performed using Minitab. Session transcripts of the analytical processing of the data in Minitab are provided in Appendix G, including detailed ANOVA results. Charts and graphs provided in the text of this Chapter were generated from Minitab.

Workload Analysis

Workload was determined to be a measure of three factors:

1. the number of actions required to complete a task (six tasks),
2. the number of tasks performed incorrectly,
3. and the perceived ability to control objects and the situation as determined by the participants in survey results.

In total there are eight factors that were considered for each run of the experiment to determine workload results (mouse clicks for each of six tasks, number of incorrectly performed tasks, and the survey results relative to workload). The number of actions required to accomplish a task was measured by the quantity of mouse clicks used to complete each of the six assigned tasks during the experiment (mouse clicks are the primary method of executing actions in the simulation). For the two experimental runs (one with the standard interface and one with the hypervariate display), the individual results are presented Figures 8 and 9.

The complete RM ANOVA results for workload data points can be found in Appendix G, a summary of the p values for each is provided in Table 1. Concerning the effect of participants performing the experiment twice, Table 1 indicates that p values for participant influence in the factors (within subjects) are greater than α (α), therefore the null hypothesis H_0 is accepted - multiple measurement of the same participant was not

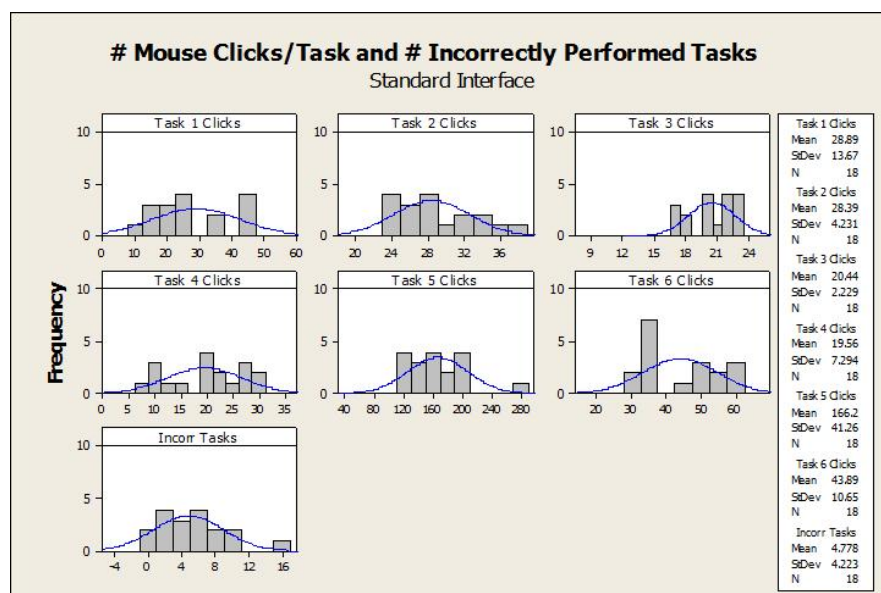


Figure 8. Histogram. Workload, Standard Interface

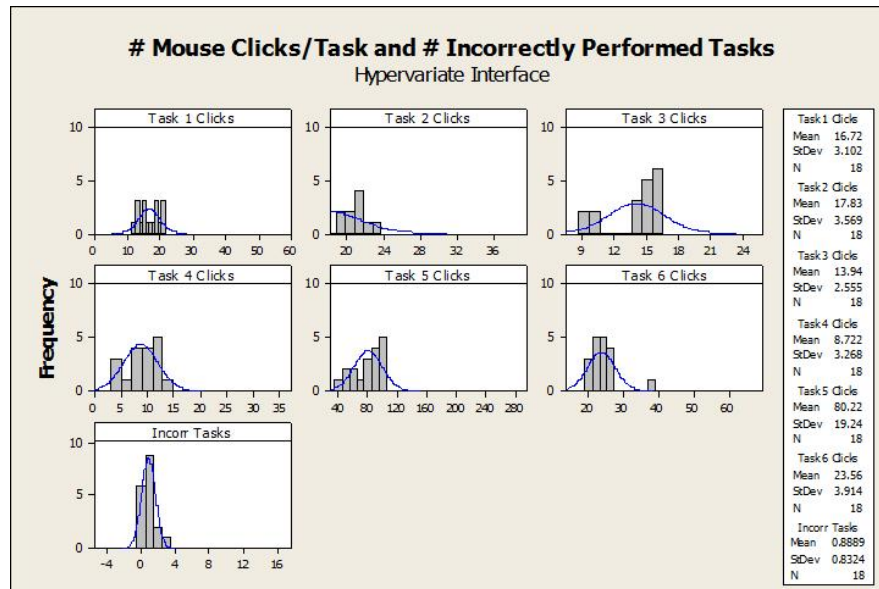


Figure 9. Histogram. Workload, Hypervariate Interface

a factor of significance in the experiment. This then allows full consideration of the quantitative indicators of workload – the number of actions (mouse clicks) necessary to accomplish the six assigned tasks and the number of tasks that are performed incorrectly.

Table 1

Probability (p) Values for Workload Factors

Between Subjects and Within Subjects

Factor	Between Subjects p	Within Subjects P
# Clicks, Task 1	0.002*	0.430
# Clicks, Task 2	0.000*	0.702
# Clicks, Task 3	0.000*	0.559
# Clicks, Task 4	0.000*	0.060
# Clicks, Task 5	0.000*	0.542
# Clicks, Task 6	0.000*	0.338
Incorrectly Performed Tasks	0.001*	0.237

* $p < .05$

The corresponding analysis of p values for the interface (between subjects) are less than $alpha$ (α), so the null hypothesis (H_0) is rejected and the hypothesis that the hypervariate display has a significant impact on the user's ability to handle large workloads.

In the experiment, all of the tasks (including the major tasks of defense and attack (Tasks 5 and 6)) required significantly fewer mouse clicks to accomplish the tasks using the hypervariate display than the standard interface. Similarly, using the hypervariate interface, a significantly fewer number of tasks were performed incorrectly. These two factors indicate that the workload placed on the operator was substantially reduced when using the hypervariate interface.

From the qualitative data, questions 2, 7, 8 and 9 (Appendix B) were relevant to the perception of the participants in how the hypervariate display improved workload. A t -test of survey results from these questions would indicate that the differences between opinions regarding the standard interface versus the hypervariate interface in question 7 were not statistically significant, so the results for question 7 were ignored. Questions 2, 8, and 9 were within acceptable criteria, are considered to be conclusive, and are therefore considered as accurate representations of user attitudes. Complete t -test results for the User Survey are found in Appendix G. On a scale of one to ten (ten was "Strongly Agree"); users averaged a score of 4.7 on whether they felt in control of the situation with the standard interface versus an average of 7.1 using the hypervariate display (question 2). Likewise, they averaged a 5.2 when asked if they felt in control of their individual units with the standard display and 7.4 using the hypervariate display (question 8).

Concerning the participant's ability to find necessary information, they averaged 7.1 with the standard display and 8.6 with the hypervariate display (question 9).

The results of both the quantitative data conclusively indicated that workload was reduced for the participants. The supporting qualitative data would bear out that the participants perceived a reduction in workload. The value plot graphically identifies the individual values of the results for each experiment, and provides an effective visual comparison of results from the two runs of the experiment. Examination of individual value plots in Figures 10 and 11 for two representative factors in workload (the number of incorrectly performed tasks and the number of key clicks to accomplish Task 5) indicate a significant reduction in both the mean and the variance in the hypervariate display versus the standard interface. The inference drawn from this data is that less work was required to accomplish the assigned tasks, and that work effort was better focused, resulting in fewer tasks that were performed incorrectly.

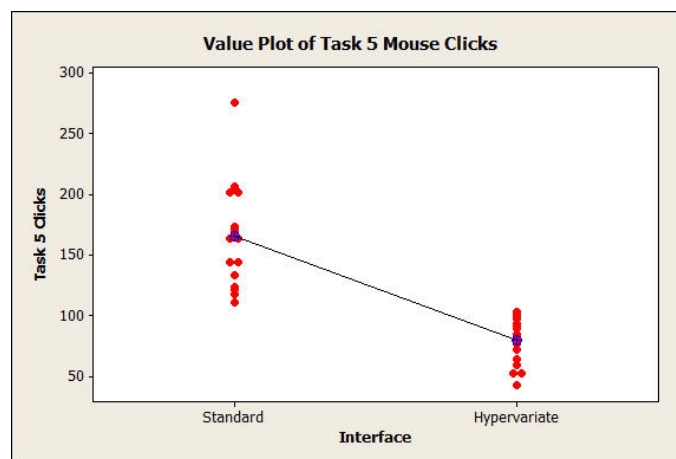


Figure 10. Individual value plot, clicks required to accomplish Task 5, Standard vs. Hypervariate displays.

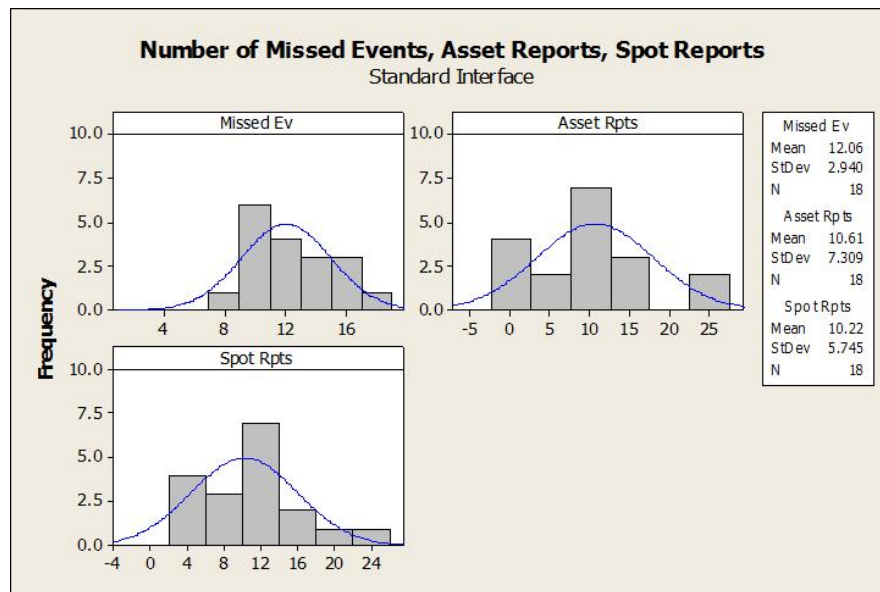


Figure 12. Histogram. *Comprehension, Standard Interface*

information regarding personnel, equipment, and supplies in a unit. Spot reports provide details regarding events relative to an exercise object.

The RM ANOVA results for comprehension data can be found in Appendix G, a summary of the p values for each factor is provided in Table 2 below. In considering the participant results (within subjects) in Table 2, one factor (missed events) was less than

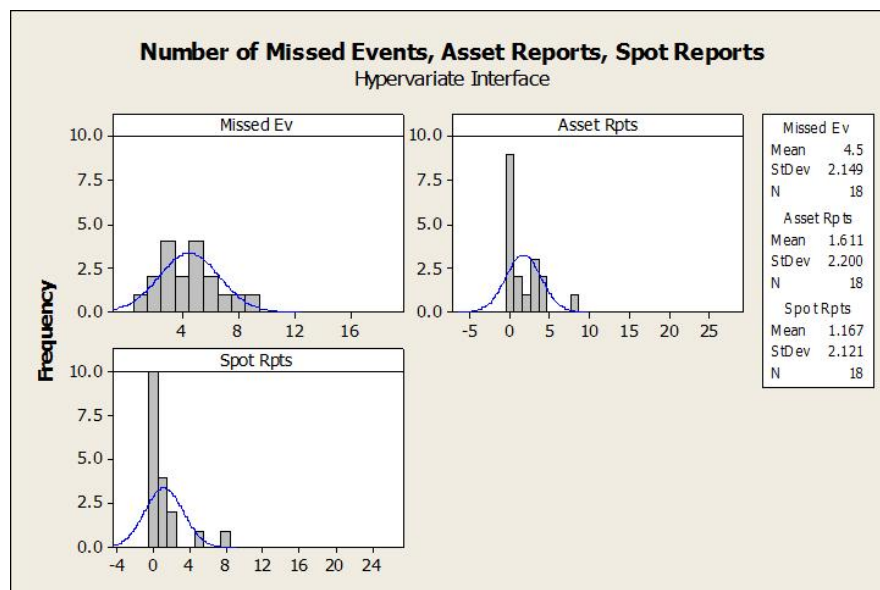


Figure 13. Histogram. *Comprehension, Hypervariate Interface*

alpha (α), indicating that H_0 should be rejected and the hypothesis supported that multiple runs of the simulation by the same individuals may have had an impact on how many events were missed. Because the same number and same kind of events were repeated in the individual runs of the scenario, it would appear that the participants were able to anticipate some of the significant events of the exercise.

Table 2

Probability (p) Values for Comprehension

Factors Between Subjects and Within Subjects

Factor	Between Subjects p	Within Subjects p
Missed Events	0.002*	0.000*
Asset Reports	0.000*	0.055
Spot Reports	0.000*	0.303

* $p < .05$

For the other two factors (number of requested asset reports and spot reports), Table 2 indicates that p values for participant influence (within subjects) in the factors are greater than *alpha* (α), therefore the null hypothesis H_0 is rejected - multiple measurement of the same participant was not a factor of significance in the experiment for unit asset requests or spot report requests. For comprehension, the quantitative factors of quantity of unit asset reports and the quantity of spot reports will be evaluated in depth while the number of missed events will not be evaluated as a significant factor. The corresponding analysis of p values for the interface (between subjects) are less than *alpha* (α), so the null hypothesis (H_0) that the hypervariate display does not have an impact on the user's ability to understand the impact of the data flow is rejected; the research is supported indicating that the means of each of the factors differed significantly. The number of reports

requested by users (both Asset and Spot Reports) indicates that there was substantially less need to request additional information when using the hypervariate display to understand the implications of the developing situations.

Ten of the survey questions (1, 4, 5, 6, 10, 11, 12, 14, 17, and 19) (Appendix B) were relevant to the overall awareness and understanding of the participant in the use of the interface during the scenario runs. A *t*-test of survey results from these questions indicates that the differences between opinions regarding the standard interface versus the hypervariate interface in questions 4, 5, 6, 12, 14, and 17 were not statistically significant, so the results for these questions are ignored for this discussion.

Complete *t*-test results for the User Survey are found in Appendix G. Questions 1, 10, 11, and 19 were within acceptable criteria and are considered to be conclusive. Ranked by the participants on a scale of one to ten (ten was “Strongly Agree”), users averaged a score of 5.0 on whether they knew the status of their units at all times on the standard interface versus an average of 8.4 using the hypervariate display (question 1). When asked if information was consistently available, the respondents’ mean was 7.0 for the standard interface and 9.1 for the hypervariate interface. Likewise when asked about critical information being available when needed, the participants’ mean for the standard interface was 6.1 while the mean was 9.1 for the hypervariate display. Finally, the mean for the standard interface was 7.1 for the question about whether they could readily find information while the hypervariate display’s mean was 8.6. The large differences in the mean responses heavily favor the hypervariate display making critical decision-making information readily available to the operator.

Even while disregarding the “missed event” factor and questions where the p value result was inconclusive for multiple runs, the results of both the quantitative and qualitative data conclusively indicated that comprehension was improved for the participants when using the hypervariate display. Even with some influence introduced by participants doing multiple runs of a similar scenario, it can be seen in Figure 14 that there was still a large difference (in favor of the hypervariate display) in the mean values between the two interfaces even if there was no difference in variance.

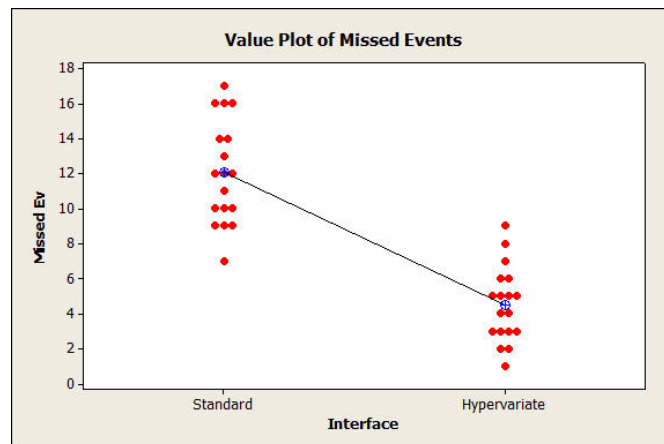


Figure 14. Individual value plot, number of missed events, Standard vs. Hypervariate displays.

The supporting qualitative data also bears out that the participants felt that they had a greater understanding of the unfolding situation when using the hypervariate display. Individual value plots (Figures 15 and 16) for two representative factors in comprehension (number requests for unit asset reports and the number of spot reports) indicate a significant reduction in mean and variance in the hypervariate display versus the standard display, indicating that operators did not require as much supplemental information when using the hypervariate display to understand the developing situation; comprehension was improved using the hypervariate display.

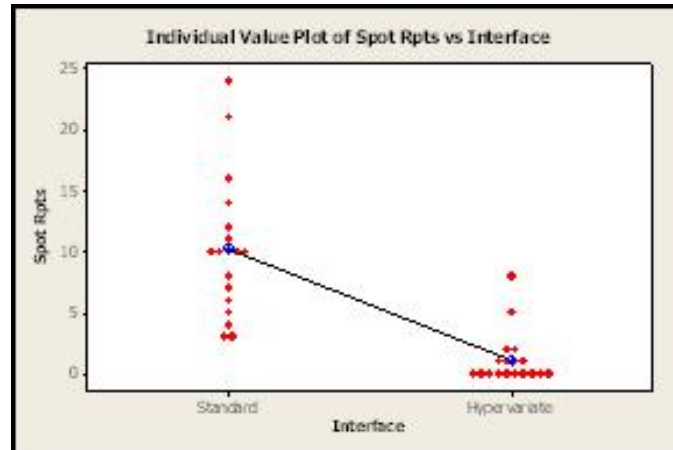


Figure 15. Individual value plot, number of spot report requests, Standard vs. Hypervariate displays.

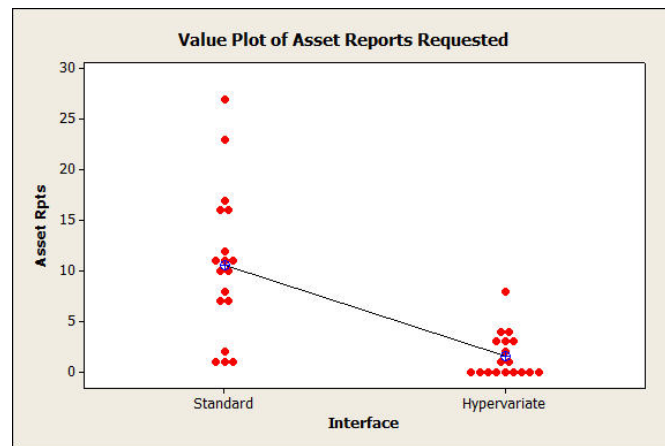


Figure 16. Individual value plot, number of asset report requests, Standard vs. Hypervariate displays.

Efficiency Analysis

Chapter 3 established efficiency as a measure of the amount of time required to complete tasks, the number of significant tasks completed in the allotted time, and the perceived level of efficiency as determined by the participant surveys. During the execution of both scenarios, six tasks were specified for the participants to perform. Of the six, two were significant enough to be of particular interest because of their complexity.

The first, defense of the coastline against an advancing enemy (Task 5) required the operator to place eight units into a defensive posture that would stop the pre-programmed advance of hostile units. Success was measured by whether the hostile units had penetrated the defensive line by the end of the scenario run (1.5 hours of game time). The second significant task was to use four units to attack and hold a key piece of terrain inland from the coast (Task 6). The task was successfully accomplished if the position was occupied by friendly forces by the end of the scenario run.

The survey also provided six questions from which user perception of efficiency could be measured. Histograms of the individual results of the quantitative factors considered for efficiency for both the standard and hypervariate displays can be found in Figures 17 and 18. The complete RM ANOVA results for efficiency data can be found in Appendix G; a summary of the p values for each factor is provided in Table 3 below. One of the four minor tasks (time to complete Task 4) had a participant p value (within subjects) that was less than $alpha$ (α), indicating that the multiple participation H_0 should be rejected

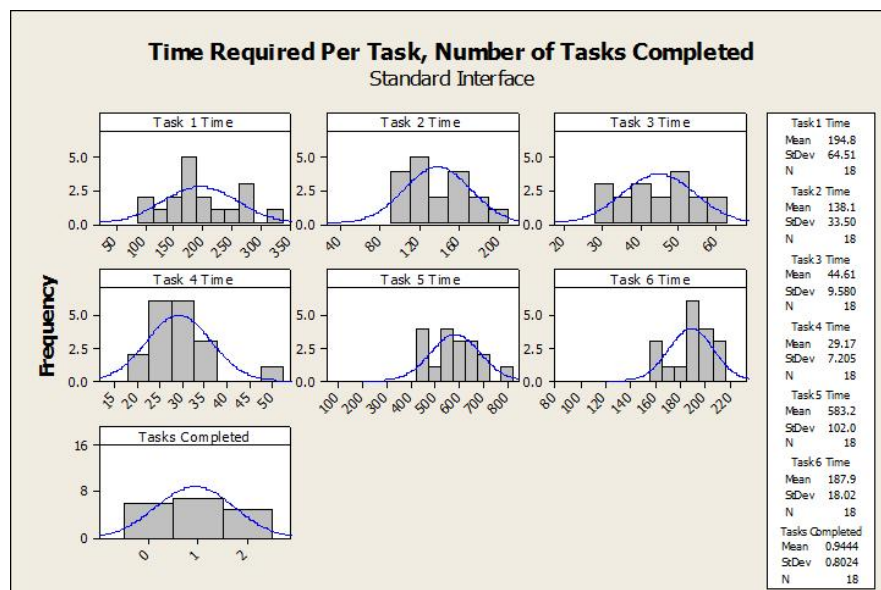


Figure 17. Histogram. *Efficiency, Standard Interface*

and the assumption made that multiple runs of the simulation by the same individuals may have had a marginal impact on how long it took to accomplish Task 4 (making it easier for the operator on the second run of the scenario).

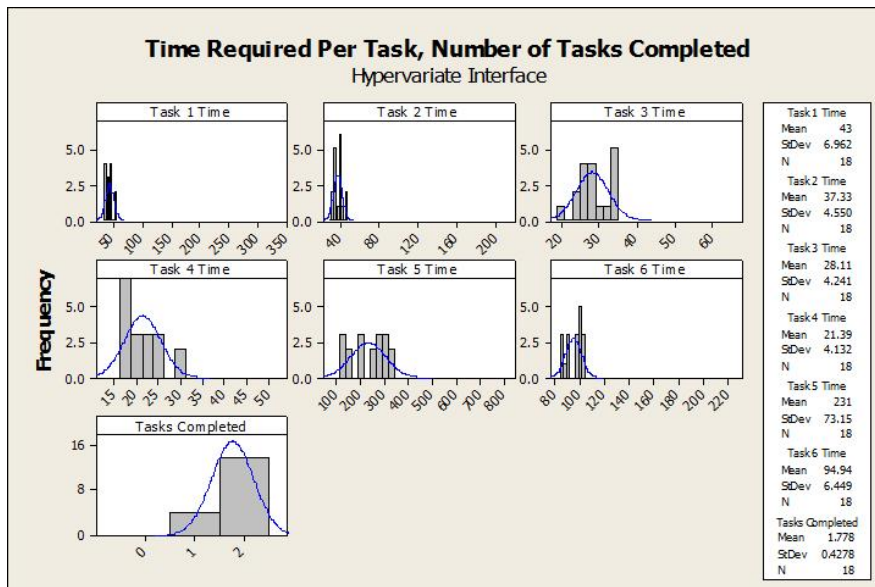


Figure 18. Histogram. *Efficiency, Hypervariate Interface*

For the remaining factors (time to accomplish Tasks 1-3, 5-6, and the number of tasks completed), p values for participant influence (within subjects) in the factors are greater than $alpha$ (α), therefore the null hypothesis H_0 is accepted - multiple measurement of the same participant was not a factor of significance in the experiment for all of the task times (with the exception of Task 4) and Tasks Completed. For the efficiency factor, these times will be evaluated in depth while the time involved to accomplish Task 4 will not be evaluated as a significant factor.

Table 3

Probability (p) Values for Efficiency FactorsBetween Subjects and Within Subjects

Factor	Between Subjects p	Within Subjects p
Time, Task 1	0.000*	0.496
Time, Task 2	0.000*	0.585
Time, Task 3	0.000*	0.264
Time, Task 4	0.000*	0.042*
Time, Task 5	0.000*	0.086
Time, Task 6	0.000*	0.465
Tasks Completed	0.001*	0.326

* $p < .05$

Across all of the factors used to indicate efficiency, the interface p values (between subjects) were less than $alpha$; the null hypothesis H_0 is rejected and the research hypothesis is supported. This indicates that there was a statistically significant difference between the time required to accomplish tasks using the hypervariate display and the standard display where operators were much faster using the hypervariate interface. Additionally, while there were only two major tasks to complete (Task 5 - successful defense of the coastline and Task 6 - successful attack of an area), it is clear from the results that when users were utilizing the hypervariate display they were much more likely to accomplish both of the key missions than if they were employing the standard interface. Figures 19, 20, and 21 show value plots of three of the efficiency factors – time to complete the two major tasks and total number of tasks completed.

For the two critical tasks (Tasks 5 and 6), it is clear that the mean time required to accomplish the tasks was reduced by half when employing the hypervariate display, and that the mean number of successful key tasks nearly doubled when using the hypervariate interface. Also of note is that while using the hypervariate display, only three of the operators failed to accomplish both of the major tasks (as opposed to six participants that failed both tasks and seven that failed to accomplish one of the tasks using the standard interface) and none of the users failed to accomplish both major tasks while using the

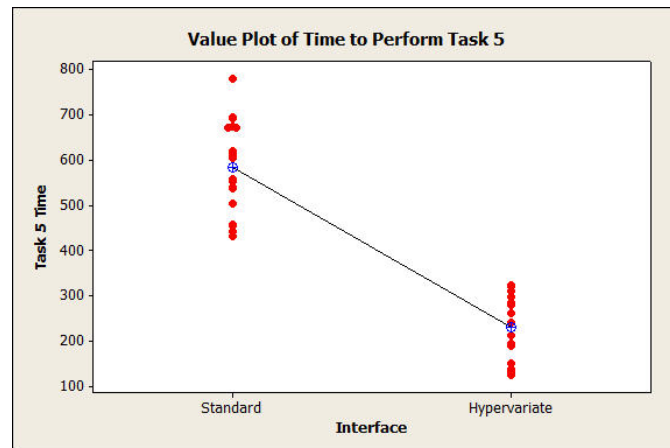


Figure 19. Individual value plot, time required to complete Task 5, Standard vs. Hypervariate displays.

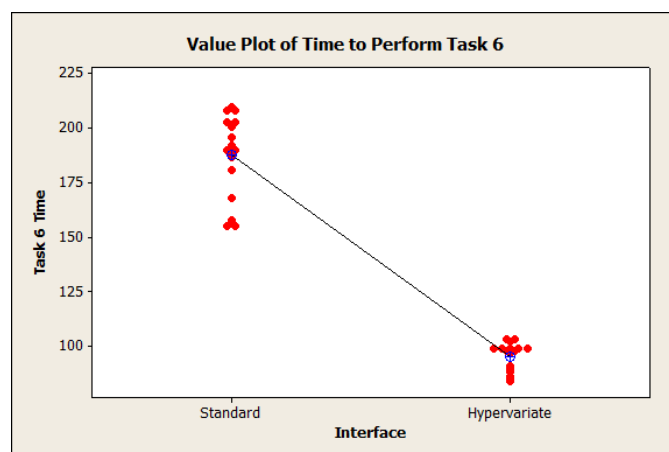


Figure 20. Individual value plot, time required to complete Task 6, Standard vs. Hypervariate displays.

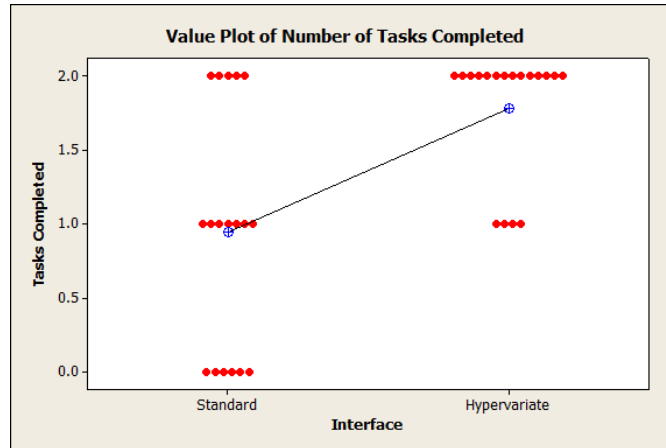


Figure 21. Individual value plot, number of tasks successfully completed, Standard vs. Hypervariate displays.

hypervariate display.

Six of the survey questions (3, 9, 15, 16, 18, and 20) (Appendix B) were relevant to the ability of the participant in the effective use of the interface to quickly accomplish assigned tasks. A *t*-test of survey results from these questions indicates that the differences between opinions regarding the standard interface versus the hypervariate interface in questions 9, 15, 16, and 20 were not statistically significant (*p* values were above α), so the results for these questions are ignored for this discussion. Questions 3 and 18 were within acceptable criteria and are considered to be conclusive. Complete *t*-test results for the User Survey are found in Appendix G. Ranked by the participants on a scale of one to ten (ten was “Strongly Agree”), users averaged a score of 5.8 on whether they could obtain necessary information in a timely manner on the standard interface versus an average of 8.3 using the hypervariate display (question 3). When asked if the user interface was easy to learn and understand, the respondents’ mean was 6.7 for the standard interface and 8.6 for the hypervariate interface (question 18). The statistically significant difference between the mean responses to the question in the two

circumstances indicates that operators felt they were better able to obtain and understand critical information with the hypervariate display than they could with the standard interface.

The results of both the quantitative and qualitative data conclusively indicate that the participants' efficiency was improved when using the hypervariate display, as evidenced by the significant reductions in mean and variance in the time required to complete tasks across the full spectrum of task assignments when using the hypervariate display versus the standard display. Further, not one of the 18 participants failed to accomplish either of the two critical tasks when using the hypervariate interface while six failed one of the tasks. This would indicate that the operators were able to more effectively accomplish their missions when employing the hypervariate interface.

Summary of Results

A simulation system was selected as the medium for experimentation so that the data types and data delivery methods were held static (i.e., controlled variables); by doing so, the ability of exercise participants to handle large volumes of information was studied in isolation. Three factors were selected to measure cognitive activity among participants: workload, comprehension, and efficiency. Each factor had several elements that were directly measured under stressful conditions to derive a quantitative measure of cognitive loading in order to compare an interface that employed hypervariate principles to the existing interface.

Participants demonstrated better comprehension, efficiency, and reduced workload when using the hypervariate display as opposed to the standard display. In most cases the data revealed significant differences in the participant's ability to accomplish assigned

tasks even when the pressure of the rapidly advancing scenario increased toward the end of each run of the experiment. More tasks were not only completed, but the completion of the tasks was accomplished more quickly and with fewer clicks of a mouse using the hypervariate interface.

Chapter 5

Conclusions, Implications, Recommendations and Summary

Conclusions

The collected data supports the conclusion that the use of hypervariate display techniques improved the operator's capacity to perform under conditions that stressed their cognitive abilities. While all of the participants had experience with the standard, preexisting interface (average of 2.5 years of experience using the standard interface in scheduled military exercises), their first and only exposure to the hypervariate display was when they were provided 30 minutes of training prior to the experiment. All of the participants showed improved performance when using the hypervariate display despite their limited exposure, training, and experience on that interface.

In contrast to the participants' performance when using the standard interface, quantitative data clearly indicated that assignments were performed faster and more efficiently using the hypervariate display and tasks were more consistently accomplished as well. Qualitative data collected through completion surveys showed that participants felt that the hypervariate interface was more satisfying to use. Comments such as "Information on battlefield events were much easier to understand. The Spot Report history on each [unit] was outstanding." and "Objects of Interest [the primary window in the hypervariate display] was helpful in quick analysis of unit activity and status – much more 'information' rather than 'data'." indicate that the hypervariate aspects of the

interface did exactly what they were designed to do – provide improved comprehension of a rapidly developing situation, and allow faster and more accurate execution of tasks based on their better comprehension.

Even in situations where the data was unclear as to the potential influence of participants doing both scenarios, there was still clear evidence that improvements occurred. In examining the data associated with the number of significant events that were not observed by the participant (missed events), the repeated measures ANOVA revealed the potential influence of the participants conducting multiple runs of the scenario, evidenced by similar variances of data points, however the mean number of missed events was 50% lower when using the hypervariate display. From the perspective of situational awareness, the hypervariate display clearly contributed to a better understanding of the data streaming to the user. Equally telling was the results of the number of key assignments that were accomplished. Only two significant tasks were assigned to the participants. Of the 18 participants, six failed to complete both of their tasks using the standard interface, seven failed to complete one task. Using the hypervariate display, none of the participants failed both tasks and only three participants failed one task.

Research Questions

In Chapter 1 of this dissertation, three research questions were suggested to address the hypothesis of this research. The hypothesis (H) of this research was: integration of hypervariate display techniques will significantly improve the performance of test subjects on specified tasks, substantially improve the operator's spatial awareness, and significantly improve operator effectiveness over the use of current display systems. The

questions were intended to address the three aspects of the hypothesis, awareness (comprehension), efficiency, and ability to accomplish goals (workload).

The three research questions proposed in Chapter 1 were:

1. What are the differences in awareness levels of operators when using a hypervariate display as opposed to using a standard display?
2. Does a computer operator become more efficient when using a hypervariate display?
3. Does a hypervariate display improve a computer operator's ability to accomplish assigned tasks?

Research question 1 studied the differences in awareness of operators when using a display that employs hypervariate principles. Would the attributes of a hypervariate display raise awareness for the participants appreciably? The research found significant positive differences in the ability of the users to discern important information from the flood of message and turn the information into appropriate and timely actions when the hypervariate interface was in use.

Research question 2 dealt with a user's ability to effectively or efficiently operate the required controls of the device to accomplish assigned tasks. With a hypervariate display, would the operator be able to get assignments done faster with less effort? It was clear from the data collected that the hypervariate display allowed the operator to accomplish tasks in less time than when using the standard display, and that many fewer mouse clicks were required to get the assignments completed. Comments made by the participants following the experiments were relevant: "Reduced keystrokes due to the OOI [Objects of Interest interface in the hypervariate display] was very helpful in controlling situation

= more time to use CE [Command Entry] to input commands.” and “I found myself doing all of my commands directly from the Objects of Interest window; much easier than finding a unit on the screen...”.

The final research question was specifically intended to address the ability of the operator to complete tasks in a satisfactory manner. Would the hypervariate interface appreciably improve the users’ ability to accomplish their responsibilities? The scenario used in the experiment was intended to gradually increase in volume of data flow and difficulty until the operator’s ability to absorb the information was saturated; thereby creating an artificial cognitive overload for the participant. From the quantitative data, the number of tasks completed provides convincing evidence that the hypervariate display did in fact increase the user’s ability to accomplish the assigned mission in spite of the very challenging environment. The data shows that fewer significant events (data points) were missed and that key tasks were more consistently accomplished when using the hypervariate display.

This study has shown that in every respect, the null hypothesis (H_0) must be rejected meaning that the fundamental research hypothesis is supported; spatial awareness was significantly improved, reaction times were substantially reduced, and performance significantly improved while using a display with hypervariate characteristics. The experiment successfully demonstrated that cognitive load was significantly reduced for operators when they were utilizing a hypervariate display.

Implications

The experimental data supports the conclusion that hypervariate display techniques had a positive effect on the user’s cognitive processing. The techniques used in this

dissertation were adapted from those suggested by Bhavnani (2000) to the MTWS user interface, incorporating known visualization techniques like preattentive processing (Healy, Booth, & Ennis, 1996) to further enhance the cognitive process. In summary, Bhavnani's strategy includes three visualization principles:

- Only relevant information should be viewed
- Allow access to viewing of distant information
- Provide global and local views for navigation, selection and manipulation (Bhavnani, 2000)

The adaptation of those principles to the MTWS graphical user interface created an interface that logically presented a wide variety of data that was filtered to the user's needs, focused on developing events, and processed into information that could be readily understood at a quick glance. Further, it provided a means to see the "big picture" while not removing the ability to view a detailed rendering at the same time. Because this research intended to apply transferable principles rather than specific user interface solutions, the implication can be drawn that the principles, when applied to other user interfaces in other disciplines would equally improve cognitive performance.

The opportunity to reduce cognitive load for system operators could provide relief to the challenges of absorbing large volumes of important information and separating necessary information from the mass of available data as discussed in Chapter 2. While cognitive load is difficult to directly measure, the results of overloading are well known to a variety of disciplines where system operator's performance is seriously impacted. In military command and control (Evans, 2005 and Onley, 2003), the challenge is to provide data processed into information that leads to timely decisions that bring successful

campaigns. The research being performed by the United States Navy in Tactical Decision Making Under Stress (TADMUS) is intended to find display strategies that can aid in promoting accurate decisions (Hutchins, Morrison, & Kelly, 1996 and Newhall, 2005) and preventing inadvertent bad decisions like the Vincennes tragedy (Evans, 2005). The approach to hypervariate visualization presented in this research has demonstrated directly how military command and control system interfaces could be improved to resolve many of the TADMUS and other command and control challenges in both the military and paramilitary environments.

In the cockpit of aircraft, the challenge is to display rapidly changing data clearly where reaction times can be reduced significantly. A typical heads-up display (HUD) and cockpit instrumentation provides the pilot with weather patterns, wind shear conditions, airspeed, altitude, approach angle, and other aircraft in traffic and approach patterns for military and commercial aircraft, in addition to providing targeting and defensive information for military cockpits (Hughes, 2005 and Starter, 2000). Research into effective multivariate and hypervariate displays is likely most advanced in the aircraft cockpit environment, but there is significant room for additional improvements where preattentive queues can reduce reaction times.

Another challenging discipline that would benefit from the application of hypervariate strategies is in air traffic control where the challenge of cognitive processing is on comprehending large quantities of complex data. “For example, the cognitive/sensory capacities required for high performance at radar workstations include spatial scanning, movement detection, image and pattern recognition, prioritizing, visual and verbal filtering, coding and decoding, inductive and deductive reasoning, short- and long-term

memory, and mathematical and probabilistic reasoning.” (International Labor Organization, 2000, ¶ 4). An interface that can pre-process data to reduce the requirement to code/decode, process, and reason will reduce the demands on a user’s short-term memory and increase the amount of potential for cognitive processing.

During the tragic events after the attack on the World Trade Center in September 2001, the emergency response personnel found it was difficult for them to maintain situational awareness (an understanding of the developing situation) as they moved from outside the buildings to the interior. Further, the findings of the National Institute of Standards and Technology determined that the emergency responders that were inside the building had poor awareness throughout the emergency. While there was adequate radio communications in most areas of the buildings, it was difficult for the emergency personnel to visualize the location of the fires, viable evacuation routes, and location of evacuees (Lawson, 2004). During the recovery operations following hurricane Katrina in August 2005, the huge amount of information that needed to be received and processed by the Federal Emergency Management Agency (FEMA) was overwhelming. Cisco Systems established emergency network services to help alleviate the information overload that was occurring in FEMA elements in New Orleans (Boyle, 2005). Emergency response personnel would benefit from the introduction of communications devices that included a hypervariate display that would provide immediate access to geographically displaced information and reduce the amount of data required to be sent over limited network paths.

A hypervariate display that employs the principles described in this research provides information (processed data) rather than raw data. With an ever-increasing quantity of

data becoming available to computer operators in a variety of situations from simple web-surfing to sophisticated aircraft control devices (Mansfield, 2008, Onley, 2003, and Berghel, 1997), the need to efficiently present that data in a form that can produce successful decisions has become imperative. This research has demonstrated that a development of a functional hypervariate interface for command and control devices is not only feasible, but very beneficial. Application of the principles supported by this research would be of benefit to a variety of communities, including aircraft control devices (cockpit and traffic control), emergency response personnel (police, fire, ambulance, etc.), and even computer game interface programmers. This is particularly true in the military and law enforcement environments where massive quantities of seemingly disjointed data must be processed very rapidly into actionable information where the consequence of a data-driven decision involves the well-being of human lives.

Recommendations

This research proves general techniques for data visualization that are transportable to a wide variety of environments that employ human-computer interfaces. There is a recognized need for user interfaces that are more efficient and responsive to the requirements of the operators of existing and emerging systems (Mansfield, 2008, Onley, 2003, Krish, 2000, and Berghel, 1997). Based on this widespread need, an expansion of this research to determine other disciplines that might benefit from the principles described herein is justified. Additionally, there is potential to expand the scope of the hypervariate interface from the principles described in this research. This section will address both aspects of potential future research.

The Boeing Company has initiated a program to provide the military with an ability to monitor and influence the distribution of supplies and materiel to stations and deployed units throughout the world. The initiative, referred to as Network Centric Logistics (NCL) has developed methods to render very complex relationships between ongoing activities in a sphere of influence over time (Cooper, 2007). Figure 22 depicts the status of 11 geographically disparate activities in relation to their percentage of achievement of the desired state over time. At a glance, an operator can clearly see which activities are progressing well and which ones require further attention. This “spider” rendering is similar to Noirhomme’s (2004) rendering of automobile accidents except that Cooper employs more effective use of preattentive features like shape and color that makes the comprehension of the situation nearly instantaneous. Adaptation of hypervariate principles described in this research to existing disciplines is an open area for future investigation.

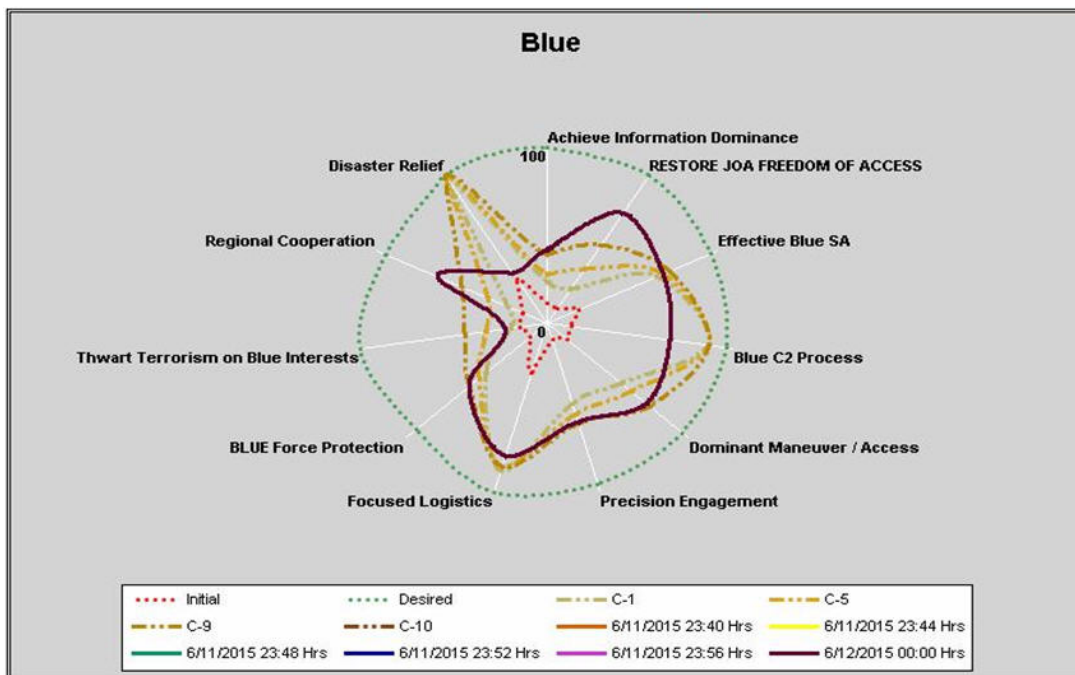


Figure 22. Blue Force Status (Cooper, 2007) with permission, The Boeing Company.

Understanding its vulnerability to information overload of its air traffic controllers, the Federal Aviation Administration (FAA) has undertaken a wide spectrum of human factors research, one area particularly suited to expanding this research is in the area of Cognitive Function Analysis. Cognitive Function Analysis focuses on determining which cognitive functions can or should be managed by a human versus handing off the functions to automation (FAA, 2008). Understanding where the appropriate balance between human and computer processing of data is could significantly improve the design of interfaces and identify what factors should be included or excluded from a hypervariate display.

An emerging area of research in human/computer interaction is Augmented Cognition. The objective of the research into augmented cognition is to “develop technologies capable of extending, by an order of magnitude or more, the information management capacity of individuals working with 21st Century computing technologies.” (Schmorrow, 2008, ¶ 2) The main thrust of the current research is focused on adaptive interfaces that would adjust the quantity and display methodology of the data presented to the user based on the user’s cognitive state in real time. When relaxed and able to process more data, the augmented display would allow more data to be presented, but when stresses are higher and less working memory is available to the user, the display would adapt accordingly (Schmorrow, 2008). A marriage of the research conducted in augmented cognition and this research would be beneficial to both investigative paths.

The emphasis of this research was on visual interfaces with the user. An expansion of the investigation into integrating other sensory aspects into the hypervariate display could prove to be beneficial. This is particularly true of audio and tactile cues. While the

hypervariate prototype developed for this research used visual signals to gain user attention (yellow highlights in the Units of Interest window), an auditory signal might have proven even more effective. Heads-up displays in aircraft cockpits use auditory warnings when the pilot's attention is required (Hughes, 2005). Raj, Kass, and Perry (2000) studied the effectiveness of the use of a tactile interface used with other factors to gain user focus in pilots involved with a hovering simulation. They determined that "Total time on target improved with tactile cueing with a significant task by display interaction. ... Results demonstrate that tactile cues can be used to improve performance in spatial tasks, such as hovering a helicopter, especially in the presence of distracting secondary workload tasks." (Raj, Kass, & Perry, 2000, p. 181). The research in hypervariate displays would benefit by determining the value of expanded sensory cueing to the system operators, particularly the areas of auditory and tactile senses.

Summary

This study investigated the integration of a number of known display principles to create a user interface that could display a large number and variety of variables to enable the operator to more effectively understand and control crucial assets and/or events. The experimentation associated with this research proved that the prototype concept successfully integrated these principles in a manner that information handling and decision-making was improved and that cognitive loading was reduced. The research further offered ideas for the potential expansion of the investigation into the reduction of cognitive loading.

This research contributes to the expanding breadth of knowledge in the area of cognition and human-computer interaction by offering empirical data that verifies

fundamental concepts for display efficiency that can be applied to future graphical user interfaces. As the quantity of data availability increases, and computing power continues to expand, the problem of too much information presented to the user too quickly will continue to grow. The application of hypervariate display techniques offers a potential solution to the challenging problems of system control when information overload occurs.

Appendix A

Starting Scenario/Participant Instructions

Participant Instructions

Your participation in this experiment is appreciated. The experiment will consist of two parts, each part will involve your control of a regimental size unit (controlled at the company level), with limited reconnaissance, artillery, and air support. Each segment of the experiment will involve 30 minutes of activity with both offensive and defensive actions; one segment using an experimental user interface add-on (Objects of Interest), and one segment performed without the add-on. The clock will be accelerated to 3:1 to increase the volume of activity during the experiment – during each 30 minute segment, 1.5 hours of activity will occur. Do not use the Objects of Interest window until instructed to do so.

While the general structure of a Marine Corps regiment has been represented, this scenario is designed to create stressful circumstances against which data can be collected; and is not intended to be tactically correct or operationally sound.

Your Task: You are the Regimental controller for the ___ Marine Regiment, with one attached section of light armor reconnaissance, one M198 Battery in direct support and two flights of FA-18C (armed with MK84 bombs) in orbit and on call (see Figure 1). Your mission is to hold defensive positions along I5, preventing access to Oceanside from the North, and to seize and hold the hospital located in the vicinity of Lake O’Neil (Objective A).

With the exception of a pre-programmed reconnaissance mission (the light armor reconnaissance), all actions to be carried out by Blue are your responsibility (movement, fire missions, diverting air missions, etc), to include defensive orders (none of the units have been assigned offensive or defensive orders at StartEx). Red actions are predetermined.

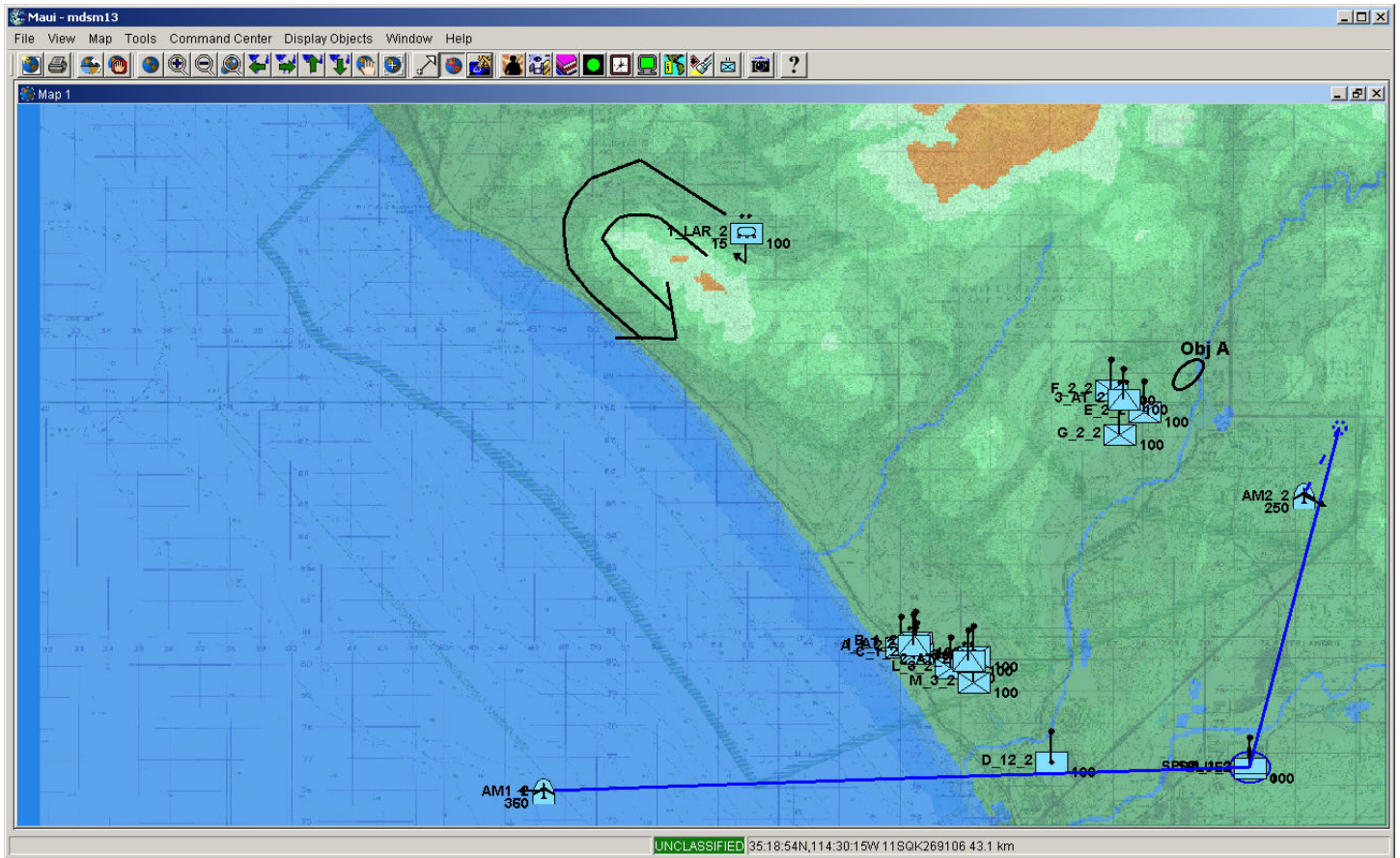
Specific Assignments:

1. Take actions necessary to accomplish the assigned task
2. Report the following events:
 - Unit Move (Start/Stop)
 - Hostile detections (visual only) and contact
 - All incoming indirect fire
 - All direct fire engagements
 - Personnel losses in excess of 10%
 - Major equipment losses in excess of 15%
 - Fire mission assessments

Reporting is done verbally. A report should follow the format provided below:

- Unit
- Exercise Time
- Location
- Event/Activity

Figure 1. Friendly Situation



Appendix B

User Survey

User Survey

Participant Number: _____

Exercise Interface (select one):
 Standard Maui Objects of Interest

Circle the number that most accurately describes your experience with the model.

	Strongly Disagree										Strongly Agree
1 I knew what the status of my assigned units was at all times.	1	2	3	4	5	6	7	8	9	10	
2 I felt like I was in control of the situation at all times.	1	2	3	4	5	6	7	8	9	10	
3 I could get the information that I required in a timely manner.	1	2	3	4	5	6	7	8	9	10	
4 I knew where to find the information I needed.	1	2	3	4	5	6	7	8	9	10	
5 I understood the information that was presented to me	1	2	3	4	5	6	7	8	9	10	
6 The available information made sense.	1	2	3	4	5	6	7	8	9	10	
7 I knew when I had to do something.	1	2	3	4	5	6	7	8	9	10	
8 I felt like I was in control of my units at all times.	1	2	3	4	5	6	7	8	9	10	
9 I could set up the windows so that I could see the information I wanted.	1	2	3	4	5	6	7	8	9	10	
10 Information was consistently available.	1	2	3	4	5	6	7	8	9	10	
11 Critical information was readily displayed.	1	2	3	4	5	6	7	8	9	10	
12 I had no trouble knowing what I needed to do.	1	2	3	4	5	6	7	8	9	10	
13 Screen space was efficiently utilized.	1	2	3	4	5	6	7	8	9	10	
14 Screen colors made sense to me.	1	2	3	4	5	6	7	8	9	10	
15 When I made a mistake, I could recover quickly.	1	2	3	4	5	6	7	8	9	10	
16 Only essential information was displayed on the screens.	1	2	3	4	5	6	7	8	9	10	
17 Help was available.	1	2	3	4	5	6	7	8	9	10	
18 The interfaces were easy to learn and understand.	1	2	3	4	5	6	7	8	9	10	
19 I felt comfortable that I could find the information I needed.	1	2	3	4	5	6	7	8	9	10	
20 I could easily control the units' actions to accomplish my mission.	1	2	3	4	5	6	7	8	9	10	

Comments:

Thank you for your participation and input!

Appendix C

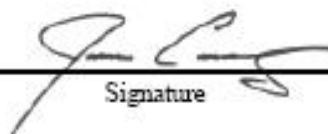
IRB Approval Memorandum



NOVA SOUTHEASTERN UNIVERSITY
Office of Grants and Contracts
Institutional Review Board

MEMORANDUM

To: William Garrabrants
From: James Connady, Ph.D.
Institutional Review Board



Signature

Date: February 15, 2006

Re: Reducing Cognitive Load Using Hypervariate Display

IRB Approval Number: connady02150603

I have reviewed the above-referenced research protocol at the center level. Based on the information provided, I have determined that this study is exempt from further IRB review. You may proceed with your study as described to the IRB. As principal investigator, you must adhere to the following requirements:

- 1) **CONSENT:** If recruitment procedures include consent forms these must be obtained in such a manner that they are clearly understood by the subjects and the process affords subjects the opportunity to ask questions, obtain detailed answers from those directly involved in the research, and have sufficient time to consider their participation after they have been provided this information. The subjects must be given a copy of the signed consent document, and a copy must be placed in a secure file separate from de-identified participant information. Record of informed consent must be retained for a minimum of three years from the conclusion of the study.
- 2) **ADVERSE REACTIONS:** The principal investigator is required to notify the IRB chair and me (954-262-5369 and 954-262-2085 respectively) of any adverse reactions or unanticipated events that may develop as a result of this study. Reactions or events may include, but are not limited to, injury, depression as a result of participation in the study, life-threatening situation, death, or loss of confidentiality/anonymity of subject. Approval may be withdrawn if the problem is serious.
- 3) **AMENDMENTS:** Any changes in the study (e.g., procedures, number or types of subjects, consent forms, investigators, etc.) must be approved by the IRB prior to implementation. Please be advised that changes in a study may require further review depending on the nature of the change. Please contact me with any questions regarding amendments or changes to your study.

The NSU IRB is in compliance with the requirements for the protection of human subjects prescribed in Part 46 of Title 45 of the Code of Federal Regulations (45 CFR 46) revised June 18, 1991.

Cc: Protocol File
Office of Grants and Contracts (if study is funded)

Appendix D

Adult Informed Consent

Adult General Informed Consent

Adult/General Informed Consent form for Participation in Hypervariate Display Study

Funding Source: None.

IRB approval # (Generated by IRB)

Principal investigator(s)
William Garrabrants
5643 Copley Dr
San Diego, CA 92111
(858) 503-1990

Principal Investigator's Advisor
Dr Maxine Cohen
3301 College Ave
Ft Lauderdale, FL 33314
(954) 262-2072

Institutional Review Board
 Nova Southeastern University
 Office of Grants and Contracts
 (954) 262-5369

Description of the Study:

The purpose of this study is to conduct research to determine the characteristics of a user interface that will reduce cognitive load on simulation operators. As a participant, you will be asked to perform two sets of tasks inside of an advancing MTWS game. The first set of tasks will be using the traditional MTWS interface, and the second set will employ a prototype interface that augments the traditional interface. Immediately preceding the use of the prototype, you will be provided with training in its proper use. Following the two sets of tasks, you will be asked to complete a questionnaire to assist in performing an accurate evaluation. The two tasks and the questionnaire will require approximately 2 hours to complete.

Because the study is intended to determine the ability of individuals to perform tasks under normal exercise conditions, it is likely that the scenario and the task lists will cause short periods of stress. The stress would be generated by rapidly developing situations, over accumulation of assigned tasks, and rapid information development.

Risks /Benefits to the Participant:

Risks to participants in this study are considered to be minimal, primarily related to stress and its health risks. There are no direct benefits from participation in this study. Intangible benefits may be derived from your participation, including future improvement of user interfaces for simulation and C4I systems, and your exposure to potential alterations to the user interface currently used by MTWS.

If you have any concerns about the risks or benefits of participating in this study, you can contact William Garrabrants or the IRB office at the numbers indicated above

Initials: _____ **Date:** _____

Costs and Payments to the Participant:

There are no costs to you or payments made for participating in this study. The USMC MTWS Support Contract will pay for up to two hours of your time spent participating in this study. Contact your Contract Administrator for assistance.

Confidentiality and Privacy:

Data collected during this study will only be used for the intended purposes listed in the description of the study (above). All information obtained in this study is strictly confidential unless disclosure is required by law. It is also possible that the Nova Southeastern University Institutional Review Board (IRB) or other regulatory agencies may examine the records. During the conduct of the study, the data will be retained in locked files and password controlled computers with access granted only to the Principal Investigator. The data will be destroyed after completion of the study unless a specific request is made by you to have your data returned to you. Should you desire to have your data returned, you may provide written notification (letter or email) to the Principal Investigator.

Use of Protected Health Information (PHI):

This study does not require the disclosure of any Protected Health Information.

Participant's Right to Withdraw from the Study:

You have the right to withdraw or refuse to participate at any time. If you do withdraw, it will not effect your current job assignments or employment circumstances. If you choose to withdraw, you may request that any data which has been collected will be destroyed (unless prohibited by state or federal law).

Other Considerations:

If significant new information relating to the study becomes available which may relate to your willingness to continue to participate, this information will be provided to you by the investigators.

Initials: _____ **Date:** _____

Voluntary Consent by Participant:

I have read the preceding consent form, or it has been read to me, and I fully understand the contents of this document and voluntarily consent to participate. All of my questions concerning the research have been answered. I hereby agree to participate in this research study. If I have any questions in the future about this study they will be answered by William Garrabrants. A copy of this form has been given to me. This consent ends at the conclusion of this study.

Participant's Signature: _____ Date: _____

Witness's Signature: _____ Date: _____

Appendix E

Experimentation Data

Partic	I/F Type	Date	Task 1	AM 1	Task 2	AM 2	Task 3	Fire Missi	Task 4	Recon	Task 5	Defense	T5	Task 6	Attack	T6	Total Run	Total Run	Total	Total	Spot	Missed	Observed	Incor Perf
			Time	Clicks	Time	Clicks	Time	Clicks	Clicks	Time	Clicks	Time	Clicks	Fail?	Time	Clicks	Fail?	Left Clicks	Rt Clicks	Events (Dia	Unit asset	Reports	Events	s (9 FM, 7 gd
1	Orig	10/29/2006	113	11	120	37	32	17	37	10	672	276	y	190	58	n	568	29	6856	23	10	9	12	6
PL1	HVD	10/29/2006	34	19	39	14	25	14	20	3	125	43	n	86	37	n	613	34	7825	4	0	2	19	1
2	Orig	10/29/2006	329	63	197	35	59	20	52	29	779	118	n	181	32	n	435	42	7349	1	4	16	5	10
PL2	HVD	10/29/2006	44	21	31	15	20	10	31	14	322	77	n	102	24	y	519	58	12459	0	0	5	16	1
3	Orig	10/29/2006	238	20	102	31	52	23	23	9	553	207	n	158	32	y	450	8	4109	2	8	10	11	3
PL3	HVD	10/29/2006	41	12	36	23	28	16	29	4	211	59	n	99	22	n	488	13	6531	0	0	3	18	1
4	Orig	11/3/2006	279	24	148	32	32	22	33	22	674	111	y	189	35	y	288	20	2895	12	5	12	9	16
mv1	HVD	11/3/2006	42	19	45	13	25	10	24	10	129	52	n	99	26	n	252	29	3691	3	2	4	17	1
5	Orig	11/3/2006	102	21	176	27	32	23	26	21	441	166	n	208	44	n	347	20	2549	1	24	9	12	6
mv2	HVD	11/3/2006	39	17	39	12	33	15	21	12	138	100	n	99	20	n	431	25	3777	0	0	4	17	1
6	Orig	11/3/2006	166	23	188	31	38	20	22	9	458	134	n	203	60	n	339	16	3566	1	10	7	14	0
mv3	HVD	11/3/2006	52	13	42	19	25	15	18	6	190	52	n	90	20	n	313	29	4171	0	0	1	20	0
7	Orig	11/3/2006	216	44	166	24	34	22	21	19	605	202	y	201	52	y	444	37	5327	7	21	9	12	1
mv4	HVD	11/9/2006	46	20	33	13	23	14	18	8	311	103	n	88	19	y	492	21	6875	1	8	3	18	0
8	Orig	11/9/2006	108	21	153	26	42	23	24	8	695	174	y	187	53	y	337	22	4684	16	14	11	10	9
cp1	HVD	11/9/2006	43	19	33	17	28	16	17	7	298	94	y	89	24	n	455	21	5612	4	1	6	15	2
9	Orig	11/9/2006	269	43	93	28	54	22	24	29	539	204	y	208	51	y	428	93	6748	17	6	16	5	1
cp2	HVD	11/9/2006	40	14	34	21	34	9	17	10	262	90	n	98	23	n	504	65	7233	8	0	8	13	2
10	Orig	11/9/2006	139	33	91	23	52	23	31	16	693	164	y	210	37	n	326	20	3291	11	11	10	11	7
cp3	HVD	11/9/2006	36	16	39	20	31	16	17	11	281	85	n	85	25	n	329	26	6576	0	1	2	19	3
11	Orig	11/9/2006	279	17	165	33	48	18	29	19	612	124	n	190	34	n	320	24	2197	8	12	14	7	3
cp4	HVD	11/9/2006	37	21	32	21	26	14	20	8	150	82	n	97	24	n	469	30	3208	0	0	5	16	1
12	Orig	11/9/2006	184	33	139	30	58	17	25	23	620	144	n	203	54	y	369	24	7157	10	10	12	9	6
cp5	HVD	11/9/2006	34	13	38	15	27	16	23	12	279	91	n	103	22	y	488	30	7147	2	2	7	14	1
13	Orig	11/9/2006	183	43	168	25	42	22	31	27	537	144	y	188	37	y	332	22	2453	27	3	16	5	0
cp6	HVD	11/9/2006	53	13	40	21	29	15	24	3	284	97	n	99	25	n	377	38	4158	3	0	9	12	0
14	Orig	11/9/2006	144	16	121	28	44	20	30	24	504	171	y	196	33	n	357	30	3247	16	10	12	9	3
cp7	HVD	11/9/2006	55	15	33	19	24	9	18	12	241	101	n	98	21	n	475	36	7182	3	1	3	18	0
15	Orig	11/9/2006	184	44	97	25	44	21	25	27	432	202	n	168	60	y	416	23	3002	11	16	17	4	5
cp8	HVD	11/9/2006	54	18	47	22	33	16	22	9	128	102	n	91	26	n	468	34	6623	0	0	5	16	1
16	Orig	11/9/2006	167	26	122	24	33	17	34	21	557	164	y	192	50	y	305	31	3285	7	3	14	7	1
cp9	HVD	11/9/2006	34	15	39	21	27	15	18	9	193	64	n	103	23	n	517	33	6200	0	5	6	15	0
17	Orig	11/9/2006	210	15	111	28	50	20	29	27	454	122	n	190	33	n	396	23	3350	10	10	13	8	1
cp10	HVD	11/9/2006	46	15	39	20	34	16	23	12	296	72	n	99	23	n	401	35	4934	0	0	5	16	0
18	Orig	11/9/2006	196	23	128	33	57	18	29	12	672	165	y	155	35	n	292	32	3535	11	7	10	11	8
cp11	HVD	11/9/2006	44	21	33	15	34	15	25	7	320	80	n	84	22	n	379	36	4241	1	1	3	18	1

Appendix F

Survey Results and Comments

		Survey Results - Standard Interface																				
		Q1	Q2	Q3	Q4	Q5	Q6	Q7	Q8	Q9	Q10	Q11	Q12	Q13	Q14	Q15	Q16	Q17	Q18	Q19	Q20	Ave
1	pl1	4	4	2	4	7	7	9	4	8	8	3	4	4	7	2	2	2	4	7	4	4.8
2	pl2	2	4	3	3	2	3	7	3	3	3	3	5	1	2	4	3	2	3	3	3	3.1
3	pl3	4	4	6	9	6	9	9	3	8	8	7	7	6	9	8	5	6	6	6	5	6.6
4	mv1	6	6	7	8	8	8	7	4	5	7	7	4	6	8	5	5	5	6	6	4	6.1
5	mv2	5	3	4	10	10	10	7	5	6	5	6	9	6	10	7	6	10	6	8	4	6.9
6	mv3	7	7	7	10	10	10	10	7	8	8	7	10	7	9	10	7	10	10	8	10	8.6
7	mv4	6	6	6	8	8	7	6	6	7	6	7	6	6	6	6	7	6	7	6	6	6.5
8	cp1	6	8	7	9	9	10	10	8	8	10	10	9	9	10	10	10	6	10	10	9	8.9
9	cp2	7	7	8	10	10	10	10	10	10	9	6	10	10	8	10	6	10	3	10	10	8.7
10	cp3	9	5	6	10	10	10	5	7	10	3	7	9	10	10	10	10	9	9	10	10	8.5
11	cp4	9	8	10	10	10	10	8	8	1	10	1	9	9	9	10	9	10	9	5	9	8.2
12	cp5	5	5	8	8	9	9	8	5	4	5	7	7	6	8	6	6	8	7	7	7	6.8
13	cp6	3	1	8	8	9	8	3	1	10	10	8	1	6	10	8	1	9	8	3	10	6.3
14	cp7	2	5	6	10	7	6	3	5	9	5	4	7	9	9	6	9	5	3	5	3	5.9
15	cp8	6	3	5	10	10	10	10	4	10	10	10	10	10	10	4	10	10	10	10	4	8.3
16	cp9	2	2	1	10	10	10	5	3	10	10	10	2	8	8	4	6	6	8	9	6	6.5
17	cp10	4	4	6	9	10	8	9	7	5	3	3	4	4	3	4	4	4	5	6	3	5.3
18	cp11	3	3	4	9	9	9	8	3	4	6	4	8	2	7	6	4	6	6	9	9	6.0
Ave		5.0	4.7	5.8	8.6	8.6	8.6	7.4	5.2	7.0	7.0	6.1	6.7	6.6	7.9	6.7	6.1	6.9	6.7	7.1	6.4	6.8

		Survey Results - Objects of Interest Interface																				
		Q1	Q2	Q3	Q4	Q5	Q6	Q7	Q8	Q9	Q10	Q11	Q12	Q13	Q14	Q15	Q16	Q17	Q18	Q19	Q20	
1	pl1	9	7	7	8	7	7	8	8	4	7	8	7	4	6	6	6	4	8	9	8	6.9
2	pl2	5	6	6	4	5	5	8	6	7	8	10	5	4	7	6	5	2	4	6	8	5.9
3	pl3	8	7	9	10	10	9	7	8	8	9	9	7	9	10	9	9	8	8	8	8	8.5
4	mv1	6	2	7	7	7	7	9	3	6	8	8	6	5	8	3	5	5	6	5	2	5.8
5	mv2	7	4	8	10	9	10	10	7	8	10	10	10	8	10	9	10	10	9	10	10	9.0
6	mv3	8	8	8	8	10	8	10	8	7	10	9	10	10	10	8	8	6	9	8	8	8.6
7	mv4	7	7	8	8	9	9	8	7	8	8	8	7	7	9	9	7	7	8	8	8	7.9
8	cp1	10	10	8	10	9	8	10	10	7	10	10	10	8	10	10	10	6	9	10	10	9.3
9	cp2	9	10	10	7	10	10	10	10	10	10	10	10	9	9	10	8	10	8	10	10	9.5
10	cp3	10	10	10	10	10	8	10	10	10	10	10	10	10	10	10	9	10	10	10	9	9.8
11	cp4	9	9	10	9	10	10	8	8	8	10	9	9	9	10	10	9	10	10	10	10	9.4
12	cp5	10	10	9	8	9	9	9	10	9	9	10	9	8	9	9	9	9	9	9	10	9.2
13	cp6	9	8	10	10	10	10	10	8	3	10	10	10	8	9	10	3	9	9	6	7	8.5
14	cp7	9	8	7	10	10	10	8	8	6	8	5	7	3	9	4	5	5	9	8	3	7.1
15	cp8	10	3	10	10	10	10	10	3	10	10	10	10	9	10	10	10	2	10	10	3	8.5
16	cp9	9	6	7	9	9	8	6	6	8	9	9	4	6	9	6	5	3	9	9	9	7.3
17	cp10	8	7	7	8	9	9	7	7	7	8	8	7	9	9	7	8	7	9	9	7	7.9
18	cp11	9	6	8	8	9	9	7	6	9	9	10	9	6	8	8	9	9	6	9	9	8.2
Ave		8.4	7.1	8.3	8.6	9.0	8.7	8.6	7.4	7.5	9.1	9.1	8.2	7.3	9.0	8.0	7.5	6.8	8.3	8.6	7.7	8.2

Survey Comments

- PL1 – **Standard I/F:** None
- Hypervariate I/F:** Biggest limitation for both tests were no screen size. It would be better if MAUI had capability for multiple monitors/screens so you could put all reports to 2nd screen and keep map and control menu on one screen.
- PL2 – **Standard I/F:** Not sure why some of the units were unable to execute their assigned missions – specifically the move & seize commands
- Hypervariate I/F:** Objects of Interest was helpful in quick analysis of unit activity and status. Much more “information” rather than “data”.
- PL3 – **Standard I/F:** The ramp-up of information when enemy detections started was fast. Did not feel like I had time for analysis and was late in taking action, maybe due to too much information
- Hypervariate I/F:** Reduced keystrokes due to OOI [Objects of Interest] was very helpful in controlling situation – more time to use CE [Command Entry] to input commands. Presentation of info in OOI helped identify threat faster and response needed.
- MV1 – **Standard I/F:** Good scenario. My difficulty in keeping up with unit actions was directly related to my inability to process all the critical information.
- Hypervariate I/F:** Am impressed with the scenario and the ease that Mac restarted the exercises
- MV2 – **Standard I/F:** Took longer to call reports and follow Spot Reports and it was hard to keep up with the activity and reports. Slower to respond due to reading Spot Report and calling SOL [Solicited] reports.

Hypervariate I/F: Lots of data in a small space of time and location. Good info available. Hard to react to all the info and still fire and maneuver units.

MV3 – **Standard I/F:** With a little more practice, I think I would do much better.

Hypervariate I/F: The new interface gave me a more detailed view of what was going on with the individual units. Also suggest a similar interface to track air missions.

MV4 – **Standard I/F:** None

Hypervariate I/F: None

CP1 – **Standard I/F:** I felt the system was very well formatted and easily done.

Hypervariate I/F: I really think this is a better way to use MTWS. I like this version of it and think as an operator we should use it.

CP2 – **Standard I/F:** Due to the amount of information on the Spot Reports and the size of the screen made it difficult to get the information I wanted.

Hypervariate I/F: The detailed ground report was a little hard to read ex: What type of unit & grid, etc?

CP3 – **Standard I/F:** I feel I need a little more experience with MTWS to get the job done but I feel I did what was needed.

Hypervariate I/F: I did a lot better. This is really beneficial for MTWS. I really enjoyed it.

CP4 – **Standard I/F:** When trying to scroll through Spot Reports FAST, I was not able to because the screen lagged out.

Hypervariate I/F: Awesome addition to MTWS. I utilized mission commands and was able to get Spot Reports I wanted using Objects of Interest.

CP5 – **Standard I/F:** None

Hypervariate I/F: None

- CP6 – **Standard I/F:** None
- Hypervariate I/F:** If the Objects of Interest were able to get my attention a little better, that would be great. The bright (yellow) on bright (white) background didn't really get my attention. If it flashed that might do better.
- CP7 – **Standard I/F:** I felt the experiment was slightly misleading. The second round seemed faster paced, the hospital was overrun before I even received a Spot Report in the first round.
- Hypervariate I/F:** The new interface is without a doubt better – but not as good as it could be. Perhaps if there was an audio alert along with the flashing yellow visual alert I wouldn't have to worry about the lack of screen space. My main complaint is that the screen is overwhelmed with boxes. I could not give mission commands, see the events of interest, see my objects AND the map at the same time. There was also a lack of access to the non-combat related info given through the Spot Reports (i.e., impassable terrain reports).
- CP8 – **Standard I/F:** Responses were slowed by lack of recent MTWS command exercises. Otherwise, information was available but much time is spent acquiring information and issuing and constructing commands.
- Hypervariate I/F:** I was not quick enough to respond although I knew what had to be done and what commands had to be used.
- CP9 – **Standard I/F:** Not enough time. Too many units to control with one workstation.
- Hypervariate I/F:** The new interface is a good tool to help filter info, but again, too much for one operator to handle/process... too many units! New interface is relatively easy to learn.
- CP10 – **Standard I/F:** It was difficult to keep up with the events on the battlefield. Trying to read Spot Reports, fire arty, fly air, call reports, move the map was too much.

Hypervariate I/F: Very interesting features. Information on battlefield events much easier to understand. The Spot Report history on each unit – outstanding. Will be great in AAR {after action review} info.

CP11 – **Standard I/F:** Too many units/Spot Reports received during this exercise period. No possible way to read them all while trying to fight the battle on the display screen.

Hypervariate I/F: I found myself doing all of my commands directly from the Object of Interest window. Much easier than finding the unit on the screen to right-click or using the CE [Command Entry] window. Pretty easy to use the new interface... however the average operator would need a bit more practice than we had.

Appendix G

Experiment Data Analysis – Minitab Output

9/8/2007 5:20:26 PM

Welcome to Minitab, press F1 for help.
Retrieving project from file: 'C:\Documents and Settings\Mac\My Documents\DISSERTATION.MPJ'

Results for: Workload(Interface = 2)**Results for Interface = 1****Results for Interface = 2****Results for: Comprehension(Interface = 2)****Results for Interface = 1****Results for Interface = 2****Results for: Efficiency(Interface = 2)****Results for Interface = 1****Results for Interface = 2****Results for: Workload(Interface = 2)****Histogram of Task 1 Click, Task 2 Click, Task 3 Click, ...****Results for: Workload(Interface = 1)****Histogram of Task 1 Click, Task 2 Click, Task 3 Click, ...****Results for: Comprehension(Interface = 1)****Histogram of Missed Ev, Asset Rpts, Spot Rpts****Results for: Comprehension(Interface = 2)****Histogram of Missed Ev, Asset Rpts, Spot Rpts****Results for: Efficiency(Interface = 1)****Histogram of Task 1 Time, Task 2 Time, Task 3 Time, Task 4 Time, ...**

Results for: Efficiency(Interface = 2)**Histogram of Task 1 Time, Task 2 Time, Task 3 Time, Task 4 Time, ...**

9/8/2007 5:24:43 PM

Welcome to Minitab, press F1 for help.
 Retrieving project from file:
 'C:\DOCUME~1\MAC\DESKTOP\DISSER~1\DISSERTATION.MPJ'

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Workload Data Analysis**Results for: Workload****ANOVA: Task 1 Clicks, Task 2 Clicks, ... versus Interface, Participant**

Factor	Type	Levels
Interface	fixed	2
Participant	random	18

Factor	Values
Interface	1, 2
Participant	1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17, 18

Analysis of Variance for Task 1 Clicks

Source	DF	SS	MS	F	P
Interface	1	1332.25	1332.25	14.17	0.002
Participant	17	1743.14	102.54	1.09	0.430
Error	17	1598.25	94.01		
Total	35	4673.64			

S = 9.69612 R-Sq = 65.80% R-Sq(adj) = 29.59%

Source	Variance component	Error term	Expected Mean Square for Each Term (using restricted model)
1 Interface		3	(3) + 18 Q[1]
2 Participant	4.261	3	(3) + 2 (2)
3 Error	94.015		(3)

Analysis of Variance for **Task 2 Clicks**

Source	DF	SS	MS	F	P
Interface	1	1002.78	1002.78	57.94	0.000
Participant	17	226.56	13.33	0.77	0.702
Error	17	294.22	17.31		
Total	35	1523.56			

S = 4.16019 R-Sq = 80.69% R-Sq(adj) = 60.24%

Source	Variance component	Error term	Expected Mean Square for Each Term (using restricted model)
1 Interface		3	(3) + 18 Q[1]
2 Participant	-1.990	3	(3) + 2 (2)
3 Error	17.307		(3)

Analysis of Variance for **Task 3 Clicks**

Source	DF	SS	MS	F	P
Interface	1	380.250	380.250	63.84	0.000
Participant	17	94.139	5.538	0.93	0.559
Error	17	101.250	5.956		
Total	35	575.639			

S = 2.44047 R-Sq = 82.41% R-Sq(adj) = 63.79%

Source	Variance component	Error term	Expected Mean Square for Each Term (using restricted model)
1 Interface		3	(3) + 18 Q[1]
2 Participant	-0.2092	3	(3) + 2 (2)
3 Error	5.9559		(3)

Analysis of Variance for **Task 4 Clicks**

Source	DF	SS	MS	F	P
Interface	1	1056.25	1056.25	59.02	0.000
Participant	17	781.81	45.99	2.57	0.060
Error	17	304.25	17.90		
Total	35	2142.31			

S = 4.23049 R-Sq = 85.80% R-Sq(adj) = 70.76%

Source	Variance component	Error term	Expected Mean Square for Each Term (using restricted model)
1 Interface		3	(3) + 18 Q[1]
2 Participant	14.05	3	(3) + 2 (2)
3 Error	17.90		(3)

Analysis of Variance for **Task 5 Clicks**

Source	DF	SS	MS	F	P
Interface	1	66564	66564	62.60	0.000
Participant	17	17154	1009	0.95	0.542
Error	17	18076	1063		
Total	35	101794			

S = 32.6082 R-Sq = 82.24% R-Sq(adj) = 63.44%

Source	Variance component	Error term	Expected Mean Square for Each Term (using restricted model)
1 Interface		3	(3) + 18 Q[1]
2 Participant	-27.11	3	(3) + 2 (2)
3 Error	1063.29		(3)

Analysis of Variance for **Task 6 Clicks**

Source	DF	SS	MS	F	P
Interface	1	3721.00	3721.00	64.42	0.000
Participant	17	1206.22	70.95	1.23	0.338
Error	17	982.00	57.76		
Total	35	5909.22			

S = 7.60031 R-Sq = 83.38% R-Sq(adj) = 65.79%

Source	Variance component	Error term	Expected Mean Square for Each Term (using restricted model)
1 Interface		3	(3) + 18 Q[1]
2 Participant	6.595	3	(3) + 2 (2)
3 Error	57.765		(3)

Analysis of Variance for **Incrr Tasks**

Source	DF	SS	MS	F	P
Interface	1	136.111	136.111	17.81	0.001
Participant	17	185.000	10.882	1.42	0.237
Error	17	129.889	7.641		
Total	35	451.000			

S = 2.76415 R-Sq = 71.20% R-Sq(adj) = 40.71%

Source	Variance component	Error term	Expected Mean Square for Each Term (using restricted model)
1 Interface		3	(3) + 18 Q[1]
2 Participant	1.621	3	(3) + 2 (2)
3 Error	7.641		(3)

9/14/2007 4:10:09 PM

Welcome to Minitab, press F1 for help.

Retrieving project from file:

'C:\DOCUME~1\MAC\MYDOCU~1\NOVA\DISSER~1\DISSER~1\DISSERTATION.MPJ'

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Comprehension Data Analysis

Results for: Comprehension

ANOVA: Missed Ev, Asset Rpts, Spot Rpts versus Interface, Participant

Factor	Type	Levels
Interface	fixed	2
Participant	random	18

Factor	Values
Interface	1, 2
Participant	1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17, 18

Analysis of Variance for **Missed Ev**

Source	DF	SS	MS	F	P
Interface	1	513.778	513.778	279.74	0.000
Participant	17	194.222	11.425	6.22	0.000
Error	17	31.222	1.837		
Total	35	739.222			

S = 1.35521 R-Sq = 95.78% R-Sq(adj) = 91.30%

Source	Variance component	Error term	Expected Mean Square for Each Term (using restricted model)
1 Interface		3	(3) + 18 Q[1]
2 Participant	4.794	3	(3) + 2 (2)
3 Error	1.837		(3)

Analysis of Variance for **Asset Rpts**

Source	DF	SS	MS	F	P
Interface	1	729.00	729.00	40.24	0.000
Participant	17	682.56	40.15	2.22	0.055
Error	17	308.00	18.12		
Total	35	1719.56			

S = 4.25648 R-Sq = 82.09% R-Sq(adj) = 63.12%

Source	Variance component	Error term	Expected Mean Square for Each Term (using restricted model)
1 Interface		3	(3) + 18 Q[1]
2 Participant	11.02	3	(3) + 2 (2)
3 Error	18.12		(3)

Analysis of Variance for **Spot Rpts**

Source	DF	SS	MS	F	P
Interface	1	738.03	738.03	45.05	0.000
Participant	17	359.14	21.13	1.29	0.303
Error	17	278.47	16.38		
Total	35	1375.64			

S = 4.04731 R-Sq = 79.76% R-Sq(adj) = 58.32%

Source	Variance component	Error term	Expected Mean Square for Each Term (using restricted model)
1 Interface		3	(3) + 18 Q[1]
2 Participant	2.373	3	(3) + 2 (2)
3 Error	16.381		(3)

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Efficiency Data Analysis

Results for: Efficiency

ANOVA: Task 1 Time, Task 2 Time, ... versus Interface, Participant

Factor	Type	Levels
Interface	fixed	2
Participant	random	18

Factor	Values
Interface	1, 2
Participant	1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17, 18

Analysis of Variance for **Task 1 Time**

Source	DF	SS	MS	F	P
Interface	1	207328	207328	98.73	0.000
Participant	17	35873	2110	1.00	0.496
Error	17	35701	2100		
Total	35	278902			

S = 45.8261 R-Sq = 87.20% R-Sq(adj) = 73.65%

Source	Variance component	Error term	Expected Mean Square for Each Term (using restricted model)
1 Interface		3	(3) + 18 Q[1]
2 Participant	5.06	3	(3) + 2 (2)
3 Error	2100.03		(3)

Analysis of Variance for **Task 2 Time**

Source	DF	SS	MS	F	P
Interface	1	91304.7	91304.7	151.82	0.000
Participant	17	9201.1	541.2	0.90	0.585
Error	17	10223.8	601.4		
Total	35	110729.6			

S = 24.5235 R-Sq = 90.77% R-Sq(adj) = 80.99%

Source	Variance component	Error term	Expected Mean Square for Each Term (using restricted model)
1 Interface		3	(3) + 18 Q[1]
2 Participant	-30.08	3	(3) + 2 (2)
3 Error	601.40		(3)

Analysis of Variance for **Task 3 Time**

Source	DF	SS	MS	F	P
Interface	1	2450.25	2450.25	52.78	0.000
Participant	17	1076.81	63.34	1.36	0.264
Error	17	789.25	46.43		
Total	35	4316.31			

S = 6.81370 R-Sq = 81.71% R-Sq(adj) = 62.35%

Source	Variance component	Error term	Expected Mean Square for Each Term (using restricted model)
1 Interface		3	(3) + 18 Q[1]
2 Participant	8.458	3	(3) + 2 (2)
3 Error	46.426		(3)

Analysis of Variance for **Task 4 Time**

Source	DF	SS	MS	F	P
Interface	1	544.44	544.44	26.55	0.000
Participant	17	824.22	48.48	2.36	0.042
Error	17	348.56	20.50		
Total	35	1717.22			

S = 4.52805 R-Sq = 79.70% R-Sq(adj) = 58.21%

Source	Variance component	Error term	Expected Mean Square for Each Term (using restricted model)
1 Interface		3	(3) + 18 Q[1]
2 Participant	13.99	3	(3) + 2 (2)
3 Error	20.50		(3)

Analysis of Variance for **Task 5 Time**

Source	DF	SS	MS	F	P
Interface	1	1116192	1116192	210.26	0.000
Participant	17	177702	10453	1.97	0.086
Error	17	90248	5309		
Total	35	1384143			

S = 72.8610 R-Sq = 93.48% R-Sq(adj) = 86.58%

Source	Variance component	Error term	Expected Mean Square for Each Term (using restricted model)
1 Interface		3	(3) + 18 Q[1]
2 Participant	2572	3	(3) + 2 (2)
3 Error	5309		(3)

Analysis of Variance for **Task 6 Time**

Source	DF	SS	MS	F	P
Interface	1	77748.0	77748.0	433.99	0.000
Participant	17	3181.3	187.1	1.04	0.465
Error	17	3045.5	179.1		
Total	35	83974.8			

S = 13.3845 R-Sq = 96.37% R-Sq(adj) = 92.53%

Source	Variance component	Error term	Expected Mean Square for Each Term (using restricted model)
1 Interface		3	(3) + 18 Q[1]
2 Participant	3.993	3	(3) + 2 (2)
3 Error	179.145		(3)

Analysis of Variance for **Tasks Completed**

Source	DF	SS	MS	F	P
Interface	1	6.2500	6.2500	17.00	0.001
Participant	17	7.8056	0.4592	1.25	0.326
Error	17	6.2500	0.3676		
Total	35	20.3056			

S = 0.606339 R-Sq = 69.22% R-Sq(adj) = 36.63%

Source	Variance component	Error term	Expected Mean Square for Each Term (using restricted model)
1 Interface		3	(3) + 18 Q[1]
2 Participant	0.04575	3	(3) + 2 (2)
3 Error	0.36765		(3)

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Welcome to Minitab, press F1 for help.

Retrieving project from file:

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Results for: Survey Results.MTW

ANOVA: Q1, Q2, ... versus Interface

Factor	Type	Levels	Values
Interface	fixed	2	1, 2

Analysis of Variance for Q1

Source	DF	SS	MS	F	P
Interface	1	106.78	106.78	31.18	0.000
Error	34	116.44	3.42		
Total	35	223.22			

S = 1.85063 R-Sq = 47.83% R-Sq(adj) = 46.30%

Source	Variance component	Error term	Expected Mean Square for Each Term (using restricted model)
1 Interface		2	(2) + 18 Q[1]
2 Error	3.425		(2)

Analysis of Variance for Q2

Source	DF	SS	MS	F	P
Interface	1	51.361	51.361	10.69	0.002
Error	34	163.389	4.806		
Total	35	214.750			

S = 2.19216 R-Sq = 23.92% R-Sq(adj) = 21.68%

Expected Mean
Square for Each

Source	Variance component	Error term	Term (using restricted model)
1 Interface		2	(2) + 18 Q[1]
2 Error	4.806		(2)

Analysis of Variance for Q3

Source	DF	SS	MS	F	P
Interface	1	56.250	56.250	16.11	0.000
Error	34	118.722	3.492		
Total	35	174.972			

S = 1.86864 R-Sq = 32.15% R-Sq(adj) = 30.15%

Source	Variance component	Error term	Expected Mean Square for Each Term (using restricted model)
1 Interface		2	(2) + 18 Q[1]
2 Error	3.492		(2)

Analysis of Variance for Q4

Source	DF	SS	MS	F	P
Interface	1	0.028	0.028	0.01	0.928
Error	34	112.722	3.315		
Total	35	112.750			

S = 1.82081 R-Sq = 0.02% R-Sq(adj) = 0.00%

Source	Variance component	Error term	Expected Mean Square for Each Term (using restricted model)
1 Interface		2	(2) + 18 Q[1]
2 Error	3.315		(2)

Analysis of Variance for Q5

Source	DF	SS	MS	F	P
Interface	1	1.778	1.778	0.58	0.452
Error	34	104.444	3.072		
Total	35	106.222			

S = 1.75268 R-Sq = 1.67% R-Sq(adj) = 0.00%

Expected Mean
Square for Each

Source	Variance component	Error term	Term (using restricted model)
1 Interface		2	(2) + 18 Q[1]
2 Error	3.072		(2)

Analysis of Variance for Q6

Source	DF	SS	MS	F	P
Interface	1	0.111	0.111	0.04	0.841
Error	34	92.444	2.719		
Total	35	92.556			

S = 1.64893 R-Sq = 0.12% R-Sq(adj) = 0.00%

Source	Variance component	Error term	Expected Mean Square for Each Term (using restricted model)
1 Interface		2	(2) + 18 Q[1]
2 Error	2.719		(2)

Analysis of Variance for Q7

Source	DF	SS	MS	F	P
Interface	1	12.250	12.250	3.51	0.070
Error	34	118.722	3.492		
Total	35	130.972			

S = 1.86864 R-Sq = 9.35% R-Sq(adj) = 6.69%

Source	Variance component	Error term	Expected Mean Square for Each Term (using restricted model)
1 Interface		2	(2) + 18 Q[1]
2 Error	3.492		(2)

Analysis of Variance for Q8

Source	DF	SS	MS	F	P
Interface	1	44.444	44.444	9.17	0.005
Error	34	164.778	4.846		
Total	35	209.222			

S = 2.20146 R-Sq = 21.24% R-Sq(adj) = 18.93%

Expected Mean
Square for Each

Source	Variance component	Error term	Term (using restricted model)
1 Interface		2	(2) + 18 Q[1]
2 Error	4.846		(2)

Analysis of Variance for **Q9**

Source	DF	SS	MS	F	P
Interface	1	2.250	2.250	0.39	0.535
Error	34	194.500	5.721		
Total	35	196.750			

S = 2.39178 R-Sq = 1.14% R-Sq(adj) = 0.00%

Source	Variance component	Error term	Expected Mean Square for Each Term (using restricted model)
1 Interface		2	(2) + 18 Q[1]
2 Error	5.721		(2)

Analysis of Variance for **Q10**

Source	DF	SS	MS	F	P
Interface	1	38.028	38.028	9.87	0.003
Error	34	130.944	3.851		
Total	35	168.972			

S = 1.96247 R-Sq = 22.51% R-Sq(adj) = 20.23%

Source	Variance component	Error term	Expected Mean Square for Each Term (using restricted model)
1 Interface		2	(2) + 18 Q[1]
2 Error	3.851		(2)

Analysis of Variance for **Q11**

Source	DF	SS	MS	F	P
Interface	1	78.028	78.028	18.08	0.000
Error	34	146.722	4.315		
Total	35	224.750			

S = 2.07734 R-Sq = 34.72% R-Sq(adj) = 32.80%

Expected Mean
Square for Each

Source	Variance component	Error term	Term (using restricted model)
1 Interface		2	(2) + 18 Q[1]
2 Error	4.315		(2)

Analysis of Variance for **Q12**

Source	DF	SS	MS	F	P
Interface	1	18.778	18.778	3.19	0.083
Error	34	200.111	5.886		
Total	35	218.889			

S = 2.42603 R-Sq = 8.58% R-Sq(adj) = 5.89%

Source	Variance component	Error term	Expected Mean Square for Each Term (using restricted model)
1 Interface		2	(2) + 18 Q[1]
2 Error	5.886		(2)

Analysis of Variance for **Q13**

Source	DF	SS	MS	F	P
Interface	1	4.694	4.694	0.79	0.381
Error	34	202.278	5.949		
Total	35	206.972			

S = 2.43913 R-Sq = 2.27% R-Sq(adj) = 0.00%

Source	Variance component	Error term	Expected Mean Square for Each Term (using restricted model)
1 Interface		2	(2) + 18 Q[1]
2 Error	5.949		(2)

Analysis of Variance for **Q14**

Source	DF	SS	MS	F	P
Interface	1	10.028	10.028	3.02	0.091
Error	34	112.944	3.322		
Total	35	122.972			

S = 1.82261 R-Sq = 8.15% R-Sq(adj) = 5.45%

Expected Mean
Square for Each

Source	Variance component	Error term	Term (using restricted model)
1 Interface		2	(2) + 18 Q[1]
2 Error	3.322		(2)

Analysis of Variance for **Q15**

Source	DF	SS	MS	F	P
Interface	1	16.000	16.000	2.78	0.105
Error	34	196.000	5.765		
Total	35	212.000			

S = 2.40098 R-Sq = 7.55% R-Sq(adj) = 4.83%

Source	Variance component	Error term	Expected Mean Square for Each Term (using restricted model)
1 Interface		2	(2) + 18 Q[1]
2 Error	5.765		(2)

Analysis of Variance for **Q16**

Source	DF	SS	MS	F	P
Interface	1	17.361	17.361	2.86	0.100
Error	34	206.278	6.067		
Total	35	223.639			

S = 2.46313 R-Sq = 7.76% R-Sq(adj) = 5.05%

Source	Variance component	Error term	Expected Mean Square for Each Term (using restricted model)
1 Interface		2	(2) + 18 Q[1]
2 Error	6.067		(2)

Analysis of Variance for **Q17**

Source	DF	SS	MS	F	P
Interface	1	0.111	0.111	0.01	0.905
Error	34	258.889	7.614		
Total	35	259.000			

S = 2.75942 R-Sq = 0.04% R-Sq(adj) = 0.00%

Source	Variance component	Error term	Expected Mean Square for Each Term (using restricted model)
1 Interface		2	(2) + 18 Q[1]
2 Error	7.614		(2)

Analysis of Variance for **Q18**

Source	DF	SS	MS	F	P
Interface	1	25.000	25.000	5.99	0.020
Error	34	142.000	4.176		
Total	35	167.000			

S = 2.04364 R-Sq = 14.97% R-Sq(adj) = 12.47%

Source	Variance component	Error term	Expected Mean Square for Each Term (using restricted model)
1 Interface		2	(2) + 18 Q[1]
2 Error	4.176		(2)

Analysis of Variance for **Q19**

Source	DF	SS	MS	F	P
Interface	1	18.778	18.778	4.90	0.034
Error	34	130.222	3.830		
Total	35	149.000			

S = 1.95706 R-Sq = 12.60% R-Sq(adj) = 10.03%

Source	Variance component	Error term	Expected Mean Square for Each Term (using restricted model)
1 Interface		2	(2) + 18 Q[1]
2 Error	3.830		(2)

Analysis of Variance for **Q20**

Source	DF	SS	MS	F	P
Interface	1	14.694	14.694	2.06	0.160
Error	34	242.056	7.119		
Total	35	256.750			

S = 2.66820 R-Sq = 5.72% R-Sq(adj) = 2.95%

Source	Variance component	Error term	Expected Mean Square for Each Term (using restricted model)
1 Interface		2	(2) + 18 Q[1]
2 Error	7.119		(2)

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