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UNITED STATES AIR FORCE RESEARCH LABORATORY

HUMAN FACTORS DESIGN ISSUES FOR SPECTRAL EXPLOITATION TOOLS

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FOR THE COMMANDER

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Increased demand for spectral data is keyed to the spectral data set's target detection potential. Spectral data can provide detailed, accurate information because of its ability to detect minuscule spectral differences in possible targets. Nevertheless, spectral-based technology has not been widely accepted or utilized in the operational community. This is primarily due to sensor collection limitations, dynamic time constraints, lack of user experience, and limited availability of validated exploitation tools and techniques.

This effort implements human factors and cognitive engineering methods to identify significant human capability issues in spectral exploitation for operational use. The report includes a proposed test and evaluation plan to assess candidate tools and techniques. Examination of current literature identified color as a critical factor in display design and the use of color in spectral displays is included as one variable in a set of real world, part task simulations. The plan also includes early, comprehensive collection of user requirements and critical decision processes to facilitate design of a field-deployable prototype spectral exploitation tool. The goal of the proposed design methodology is to enhance interpretability and decrease exploitation time in rapid precision targeting scenarios.

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PREFACE

This project was accomplished for the Air Force Research Laboratory (AFRL), Human Effectiveness Directorate, Crew System Interface Division under Air Force under SBIR Phase I, Contract F41624-99-C-6017. The effort was initiated and managed by Mr. Gilbert Kuperman, (AFRL/HECA). The authors wish to thank him for his support and guidance in the accomplishment of this effort.

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INTRODUCTION

The Problem

Current spectral analysis techniques are unwieldy in operational scenarios. This poses a challenge to the use of spectral data in Rapid Precision Targeting (RPT). Voluminous and complex sensor data sets pose technical difficulties, but only a fraction of the bands in a hyperspectral data cube are typically needed to discriminate materials of interest for any given application. A current effort in sensor exploitation technology is the development of distillation techniques to identify bands providing optimum target discriminants and reduce the data set to those bands. Once integrated into military exploitation systems, distillation techniques will sufficiently simplify the manual processing task to make plausible the visual, or spatial, exploitation of spectral data in tactical applications.

Besides the benefits to be derived from reduction of data irrelevant to the accomplishment of typical military operations, there are visualization and display issues that, once resolved, will also provide a positive impact on the employment of spectral data in operational scenarios. This report describes the results of research into current technical literature and experimental findings discussing a number of factors that impact the analyst's visual performance in spectral data exploitation for military operations. The purpose of this research has been to develop a sound basis for the design of an operational user-oriented spectral exploitation workstation. Research into current and developmental exploitation systems, both commercial and military, has determined promising system component characteristics for eventual incorporation in a prototype tactical decision aiding system.

During the effort, visualization techniques and visual display technologies were examined to identify candidate display methods for test and evaluation. Examination of visual psychophysics experimental result reports (including visual search behavior and target search strategies, color vision applications, and coding schemes) isolated candidate variables for testing during scenario-based prototype trials. This report comprises the results of the exploratory research and a high-level task analysis on a sample tactical intelligence task. The latter has been developed to direct further user requirements analysis.

This report presents the preliminary research required to support the development of user-based requirements for a concept spectral exploitation workstation and recommends a multi-phase series of experiments whose results will support the design of an effective decision aid.

Background

Remote spectral sensors (space-borne satellite systems and airborne surveillance and reconnaissance equipment) collect the emissive or reflective electromagnetic energy from objects of interest on the face of the earth and from its atmosphere. Currently, spectral sensor collection technology is divided into three levels: multispectral, hyperspectral, and ultraspectral. Multispectral satellite-borne sensors provide god's-eye views of earth activities, potentially collecting data from tens of bands of the spectrum. Hyperspectral data is collected from hundreds of narrower spectral bands and portrays more subtle variation in spectral signatures. Ultraspectral sensors collect from thousands of even narrower bands within the same ranges, and distinguish commensurately higher spectral resolutions (SITAC, 1995).

Imaging spectroscopy, the graphical analysis of quantitative spectral data, exploits beyond the visible spectrum and includes the near infrared and short, medium and long wave infrared regions. Spectral signature analysis supplements the spatial analysis of pan-chromatic imagery, providing information about the character of terrain and vegetation, as well as the man-made objects found therein. The analysis of spectral data is used to classify targets; band-to-band, target-unique information provided by higher spectral resolutions enables spectral scientists to identify targets by spectral shape alone. A common method, spectral matching, involves quantification of spectral signatures, pixel by pixel. Those signatures are compared against existing spectral signature databases collected for both natural and man-made substances. The pixel data also forms the basis for extrapolating a computer-generated non-literal image. Spectral sensing and exploitation technology adds a new dimension to intelligence collection and is viewed as a promising response to expanding military intelligence requirements.

Hyperspectral imagery (HSI) is of keen interest to government and commercial users because it provides higher discrimination potential than multispectral data or panchromatic imagery, and it is thought to provide critical information that cannot be obtained in any other remote fashion. To date, hyperspectral data has largely been confined to research efforts, in part because system designers and those developing concepts of operation for its use have been faced with numerous obstacles to its efficient employment. The huge volume of data that would need to be collected over the thousands of targets of intelligence interest becomes overwhelming to transmit and store. The exploitation of this volume of data is daunting, if not impossible, to envision in this era where intelligence requirements continue to increase even though the human resources needed to satisfy them have been reduced.

As spectral technology evolves, it is an increasingly important military intelligence asset. Improved spatial resolution—close to 1 meter or better ground sampling distance (GSD)—provides information critical to both strategic planning and tactical operations and concomitant advances in communications technologies permit the rapid dissemination of spectral data (SITC, 1997). However, the exploitation of spectral data for military purposes poses a set of challenges in terms of effective exploitation system design. Dissemination of spectral products in near-real time is hampered by exploitation capability limitations, and therefore, despite its acknowledged promise, current spectral based technology is neither widely accepted nor widely utilized in the operational community.

There are a number reasons for the reluctance to embrace spectral systems: limitations in literal image detection ranges, sensor limitations, user inexperience, and availability of tactical sensor data and validated exploitation tools and methods. However, regarding spectral exploitation, the most difficult problems faced by today's operational intelligence analyst are the revolution in exploitation philosophy, coincident with demands for increased timeliness and accuracy. Exploitation of spectral data requires traditional imagery analysts to modify their entire thought process. While traditional imagery and spectral data are both composed of thousands of pixels, the methods for interpreting the pixels are quite different. In traditional imagery exploitation, the analyst reviews the pixels that form the image as a complex, whole spatial relationship. Select compositions of pixels in an image form discrete viewable objects. Typically, most viewers interpret an image based on how individual pixels together form a complete picture. In spectral exploitation, almost the opposite is true. The analyst must break down the composition of each pixel and examine the components within—this is not an intuitive process for the traditionally trained image analyst. Nor is tactically oriented spectral exploitation training currently available in military intelligence analyst training programs. Existing commercial training programs neither support tactical (as opposed to detailed scientific) exploitation, nor are they part of the analyst's normal training opportunities.

Finally, the spectral pixel decomposition process described above yields data that is precise in nature, but in an RPT scenario—using current exploitation tools—is far from timely. Conversely, the spatial analysis of spectral data may become timely, yet remain insufficiently accurate for targeting purposes. For instance, the benefits derived from precise knowledge of the spectral components on a pixel-by-pixel basis will be limited if inability to georectify the scene impedes accurate location of the target. Joint application of both spatial and spectral exploitation techniques, therefore, may prove the most advantageous method for future intelligence endeavors and advanced analysis problem sets, and such scientific visualization-based technological advances as can be implemented to assist the analyst in the fusion process bear consideration.

During the last ten years, DoD has displayed significant interest in improvements in dynamic targeting, bomb damage assessment, re-locatable target tracking, weapons of mass destruction detection, and concealed target exploitation. Progress in these areas has brought about a noticeable increase in both sensor development and enhancements. Upgrades have occurred in the U-2 program, including radar imagery improvements, and the Senior Year Electro-optical Reconnaissance System (SYERS) has entered a Pre-Planned Product Improvement (P3I) cycle. New emphasis is being placed on overhead systems and unmanned sensors, such as Global Hawk and Predator. Amongst this rapid influx of technologies are new spectral sensor programs. The data collected by these sensors fall within the realm of Measurement and Signatures Intelligence (MASINT). MASINT is defined as

> "Scientific and technical intelligence information obtained by quantitative and qualitative analysis of data (metric, angular, spatial, wavelength, temporal modulation plasma, and hydromagnetic) derived from specific technical sensors for the purpose of identifying distinctive features associated with the source, emitter, or sender and to facilitate subsequent identification and/or measurement of the same" (Central MASINT Office, 1998).

MASINT presents to the warfighter phenomenology observations not normally observable in nature, thereby creating a new science of observation and exploration studies. The introduction of this technology brings a new and much needed capability but exacerbates the "information overload" problem faced by today's intelligence analysts. Table 1 on the following page, which shows some of the existing and projected sensors, illustrates the scope of the problem.

Concurrent with the increase in both sensors and capabilities is the emergence of another phenomenon—the shortage of qualified analysts. The military drawdown has prompted many senior military intelligence analysts into early retirement, thereby dropping the average experience level. An increasing need for experienced spectral analysts in the civilian sector also encourages many Imagery Analysts (IAs) to leave the military and test the civilian market. Nor is the number of military analysts expected to increase in the foreseeable future. In consequence, the military's exploitation capability is outpaced by the growing quantity of electro-optical (EO) and radar imagery currently being collected, which is estimated to be in the terabyte range on a daily basis and is rapidly approaching critical volume. The addition of multiple sources of spectral data will further compound the problem.

The IA shortage and the influx of all types of sensor data are not the only impediments facing military intelligence planners. The trans-service lack of tactical experience in spectral data exploitation will have a significant impact on analyst information overload. Spectral technologies are still relatively new; there is still insufficient operational understanding of spectral information's tactical potential and how best to tap it. Traditionally, IAs' primary sources of exploitable imagery have been EO and radar; most IAs have worked or trained with some form of infrared imagery. As discussed earlier, the exploitation complexity of HSI and ultraspectral data (USI) far exceeds that of literal imagery and requires exploitation techniques, currently still under development, in which IAs will have to be trained.

Until now, most spectral exploitation has supported civilian activities such as agricultural analysis, oceanic research, and natural resource mapping. Such utilizations are not time-critical and the exploitation techniques developed for them are relatively lengthy and iterative in nature—imminently unsuitable for tactical employment. Not only are there relatively few analysts who are qualified to interpret or exploit HSI/USI—if the exploitation process itself cannot support time critical timelines, it is of little to no tactical operational value.

The most comprehensive exploitation of spectral science requires trained scientists performing detailed, time-consuming analysis. Currently, spectral products are exploited by university researchers, government agencies (e.g., U.S. Geological Survey) and by a growing number of commercial imagery providers. U.S. Air Force intelligence analysis is performed at the national level by NAIC, a component of the Air Intelligence Agency. Headquartered at Wright-Patterson AFB, NAIC military and civilian scientists exploit data provided by national sensor systems. NAIC analyses are incorporated into integrated, tailored intelligence assessments and are provided to national policy makers, acquisition programs, and operational forces. NAIC analysis and product dissemination occurs within a days-to-weeks timeframe (NAIC, 1999).

Table 1. Existing and Projected Spectral Sensors

	No. of Channels	Sensor	Ground Res	Pan	Blue	Green	Red	NIR	SWIR	MWIR	LWIR
SYERS P3I	7		-	X		X	X	X	X	X	
AVIRIS	224		1mr		X	X	X	X	X		
HYDICE	210		.5mr		X	X	X	X	X		
WARFIGHTER-1	TBD		<5m		60 (minimum) at 400-2500nm						
LANDSAT-7	7		30m	1							
			60m		1	1	1	1	2		1
LANDSAT-5	7	TM	30m 120m		1	1	1	1	2		1
	4	MSS	82m			1	1	2			
QUICKBIRD-1	1	PAN	.82m	1							
	4	MSI	3.28m		1	1	1	1			
QUICKBIRD-2	1	PAN	.82m	1							
	4	MSI	3.28m		1	1	1	1			
CARTERRA-1	1	PAN	0.8m	1							
	4	MSI	3.3m		1	1	1	1			
CARTERRA-2	1	PAN	0.8m	1							
	4	MSI	3.3m		1	1	1	1			
ORBVIEW-2	8	SEA-STAR	1100m/ 4000m		2	3	1	2			
ORBVIEW-3A	1	PAN	1,2m	1/1							
	4	MSI	4m		1	1	1	1			
ORBVIEW-3B 1st Q 2001	1	PAN	1m	1							
	4	MSI	4m		1	1	1	1			
RESOURCE 21 1st Q 2000	4	MSI	10m		1	1	1	1			
	1		20m						1		
	1		100m						1		

N.B. In addition, the French reconnaissance satellite, Helios 1, has a reported 2-meter resolution capacity; the IKONOS satellite, a commercial venture launched in September 1999 by Space Imaging, has 1-meter panchromatic resolution and 3.28 multispectral resolution capabilities (Anselmo, 2000).

At 1 meter resolution, imaged objects 1 meter or greater in size and at least 1 meter apart can be distinguished one from another.

Theater and tactical intelligence exploitation of spectral sensor data is projected to be performed at the Joint Intelligence Centers (JICs), Joint Analysis Centers (JACs), Major Command levels, the Joint Task Forces (JTFs), and intelligence wings and squadrons, etc. These units are tasked as the principal intelligence elements supplying intelligence support to the operational commanders. At the JTF level, the Joint Intelligence Support Element (JISE) manages collection, analysis, and fusion of intelligence and dissemination of products up and down the echelon of intelligence for the joint operations area. While national level intelligence support has more lenient response requirements, supporting tactical operations can require an analysis and product dissemination timeframe of minutes to hours (*Joint Pub 2-0*, 1995).

The warfighter at the unit level is the ultimate recipient of spectral sensor-based intelligence. Warfighters include special operations forces, infantry squads, and ship, tank, artillery, and aircrews. While the warfighters differ considerably in their tasking, and therefore, in their sensor data requirements, none of them are likely to be able to spare resources for extended analytical processing. In conflict scenarios, the warfighter may operate in a compressed timeframe of minutes to seconds. For maximum effectiveness, products provided to the warfighter must be tailored. They must be clear, concise, and cogent; they should require minimal analysis. Possible limited analysis might conceivably include decisions on a product's relevance or irrelevance to a rapidly changing operational situation, on the validity or lack of validity of the source or of the transmission (due to information warfare activities or information transmission problems), and finally, on whether to use it or not use it. In time-critical operational settings, no further analytical demands should be placed on the warfighter.

It is clear that the momentum of information superiority is rapidly forcing the Intelligence Community into the realm of spectral analysis. However, although spectral sensors and technologies are under development today, they have not fully left the experimental stage. Because of the broad range of potential uses offered by spectral data, there exist neither a clear understanding of spectral capabilities nor a spectral data employment plan. As users are educated about HSI/USI, the number and variety of spectral data users and their requirements for information will continue to expand. The rich possibilities presented by readily available spectral data create a broad military customer base. A distributed intelligence architecture creates a geographically distributed set of locations to which spectral data may be sent—where its utility will become the responsibility of analysts whose experience with and proficiency in exploitation of spectral data ranges from novice to expert.

Diversity of analyst experience level and distribution of analytical centers, whose products conceivably may support members of all services in all operational endeavors, create a labyrinthine set of exploitation system requirements. Spectral data analysis is sufficiently new that the question of how optimally to present spectral data for rapid exploitation requires intensive study. Diversity of analyst experience levels and training opportunities and already pressing data overload issues demand careful consideration, as well. Dissimilar exploitation purposes, processes, and products further complicate spectral exploitation system design and indicate the need for intensive and focused investigative research.

RESEARCH OBJECTIVES

The research done in support of this effort had several objectives: 1) to conduct a literature search on potential human factors research shortfalls regarding the exploitation of spectral data, 2) to investigate state-of-the-art technology in spectral data exploitation, and 3) to gain a credible understanding of spectral data user needs in order to determine high payoff study factors. Key areas of research included identification of current and future spectral systems and exploitation strategies, as well as identification of visual psychophysics-based user display techniques and how they may augment current spectral analysis. This research supported a brief study of baseline spectral exploitation capabilities. It also supported the development of an initial task analysis of a sample mission. The research results directed the development of a set of recommendations for a multi-phase test plan to study the effect of spectral exploitation strategies on operational user performance. The recommendations include baseline performance studies, an incremental enhancement effectiveness evaluation process, and a user requirements study.

The following sections provide a brief overview of human factors issues and research results relating to visual display. However, while in some instances the *results* directly support visual display design, in many instances, the *issues* must stand alone. Research into the psychophysical function of the visual system is itself not yet complete and applied human factors research on aspects of vision function and the effects of presentation format may prove specific to the type of imagery used. Basic research into visual functions may be generalized, but specific applied research into interpretation of radar or infrared (military) imagery or x-ray (medical) imagery may or may not be applicable to interpretation of spectral data, as both the image displays themselves and the quantitative data intrinsic to the form of collection are considerably different in nature (i.e., multiple spectral bands vs. radio frequencies vs. heat signatures vs. x-ray absorption). Further, with ever-lengthening strides in the progress of visual psychophysics research, the available body of visual display research shows a commensurate growth curve.

An additional consideration is the relevance of the research methods. Investigations in target search can be (very roughly) divided into two research designs: those in which the subject searches for a shape within a field of analogous shapes (target search in simple images) and research designs in which the subject searches for a shape within a field of complex, overlapping shapes (target search in embedded images). Within those designs, interest is split between identification of recognition factors and identification of visual search strategies. Refinements of these research designs include investigations of the effects of enhancements—presentation angle, color coding, highlighting, cueing boxes—and how their use affects the target search process, as well as investigations into the effects of impediments—clutter, poor contrast, poor resolution. That *all* such research results are directly applicable to spectral data set target search activities is probably an incorrect assumption. What is presented in the following sections as applicable to spectral imagery interpretation is proffered with the caveat that only through the collection of empirical evidence (an essential next step in image analysis research) can one *prove* which portions of existing results can be applied in effective spectral exploitation system design strategies. In the absence of such evidence, one can only extrapolate from existing data.

Human-System Interface for Spectral Exploitation

The potential utility of spectral data lies in the magnitude of the data simultaneously carried in multiple spectral bands. Hundreds of bands provide a wealth of interpretable spectral information for each individual pixel imaged, limited only by the sensor's resolution capabilities. The challenge posed by spectral exploitation is of equal magnitude. Exploitation of the information presented, whether expressed quantitatively as tabular or charted values or expressed qualitatively in thematically mapped images, is constrained by the individual analyst's processing capabilities. As earlier discussed, the individual analyst's processing capabilities are, in turn, constrained by the demands and limitations imposed by his or her operational level. The answer to the question of how to best address the exploitation design issues posed by emerging spectral capabilities is not to be found within remote sensing technology itself, nor can it be found within the engineering technologies that support spectral data transfer, processing, and display. The human-system interface (HSI)—the hardware and software configuration *as experienced by the analyst*—is the crux of the design effort, and functional exploitation workstation design depends equally upon the acquisition of a thorough understanding of the analyst and a thorough understanding of the analyst's operational responsibilities.

Effective spectral exploitation workstation HSI design has two drivers. One driver is the analyst's own capabilities: physical, perceptual, and cognitive. Human factors science—including vision research and visual psychophysics, mechanisms of perception and perceptual processing, and cognitive and decision process analysis—addresses investigative needs and suggests methods of inquiry. The use the analyst will make of the workstation is the other driver. Cognitive engineering methodology—determining how the workstation serves the analyst's task requirements and how, ultimately, it serves the intelligence customer's information requirements—also shapes the design process. Together, the human factors and the cognitive engineering disciplines provide a comprehensive approach to optimal system requirements development.

HSI encompasses a range of issues. HSI includes the physical interface, that is, the type of interface device (ranging from the typical 2-D screen display and mouse presentation through total immersion virtual environments), as well as its resolution capability, its size and position relative to the operator, the ambient lighting, and other ergonomically based issues. However, a major component of HSI is software design. HSI considerations include identification and implementation of design strategies to develop effective, efficient, requirements-based software. The HSI design objective is robust software that meets all operational user requirements, is intuitive (easy to learn and easy to use), and increases operator performance in both precision and rapidity.

A recent study performed by the National Missile Defense (NMD) program illustrates the importance of HSI design in system development (Armstrong & Steinberg, 1998). The NMD compared operator performance results for Command and Control (C2) prototypes based on user-centered design against those obtained for existing equipment based on data-centered design. During tests of data-centered design prototypes, evaluators found that operators consistently requested more data, which in turn, drove designers to search for data-centered solutions. However, analysis of operator performance during simulations showed that information requests reflected not a so much a lack of available data, but rather, the ineffective presentation of data already available. Operators could not easily discern the utility of data presentations when they were not mapped directly to user tasks or decision-making activities.

Spurred by the operator feedback and results analysis, developers initiated comparisons of operator performance in both short and long NMD task scenarios employing prototypes based on user-centered design vs. existing data-centered designs. The user-centered design prototypes reflected the importance of data presentation, both in terms of improved task support and in terms of cleaner display and faster navigation. In the comparison performance tests, operators using prototype displays developed around user requirements reduced task time by 10 percent and operator error by more than 50 percent. An additional benefit was noted in the comparison of operator experience level, which averaged 130 hours on the existing systems, but less than 1 hour on the prototype displays.

Figure 1 on the following page compares the data-centered design process flow with that of user-centered design. It is clear that user-centered design, in pulling its requirements from the user and basing its design iterations on prior task analysis, is likely to meet operational requirements earlier than data-centered designs and to require less redesign upon deployment in the "find and fix" stage. The cost benefits of well-planned design are a less costly design cycle, a more robust product, and enhanced operator performance.

Missing from the original diagram, but implicit in human factors engineering, is the concept that human capabilities must constrain the design. To that end, a box describing the determination of applicable human factors issues has been added early in the cycle in order to ensure that the user's *capabilities* are considered along with the user's *purposes*. Psychophysical constraints are user capabilities that, when allowed to influence system design, make a system easier to use and less fatiguing—and make user response more timely and more accurate.

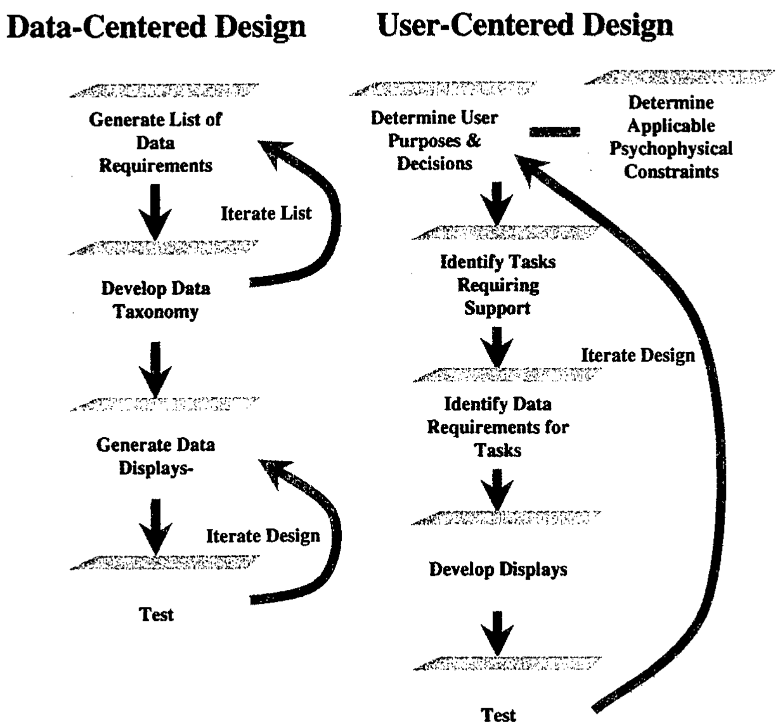

Figure 1. Data-Centered Design vs. User-Centered Design (adapted from Armstrong & Steinberg, 1998).

The iterative process of the user-centered design model guided the development of the multi-phase study plan produced for this research effort. The performance of a preliminary, high level task analysis was a critical component of a methodology developed, as previously noted, to gain a credible understanding of spectral data user needs *at the beginning of the design process*. The experimental methodology was further guided, by the anthropologically based concept of "cognition in the wild," a term coined by Hutchins (1995), in his work for the U.S. Navy, to express the importance of observing the human actor in his/her natural environment. Hutchins asserts that field observation is essential to capture the full flavor of the tasks performed—the objectives for all mission elements, the entire communications network involved, the "customers" for whom products are generated, and the "culture" of the community—thus permitting the most complete capture of user requirements. In this initial contribution to the creation of an effective design plan, the first step was to identify applicable research issues and existing instructive research results.

Human Factors/Cognitive Engineering Research Issues

A review of the human factors literature shows that basic research is ongoing in the areas of vision, perception, cognition and decision-making. Sufficient groundwork exists, however, to support applied research. Current vision and perception research distinguishes between the simple target scene, where the target is a discrete entity among other entities, and the complex, embedded target scene, where other elements in the scene visually overlap the target. Luminance and color-coding, edge and contour detection, shape shading and texture analysis, as well as other depth perception cues, are all current topics of embedded target detection research. In addition, the effects on operator performance of the use of color in imagery, including the presentation of varied hues, saturations, and chromatic combination options, continue to be subjects of applied target detection research.

While research has been and is yet being done on target detection tasks and on imagery analysis, the results are not necessarily all *directly* applicable to spectral data analysis. Spectral data-based "imagery", depending as it does upon quantizations across multiple spectral bands, is not of the same "literal" character as single sensor electro-optical imagery. However, there are circumstances in which the *visual* analysis of a spectral data-based image probably is sufficiently analogous to traditional visual imagery analysis to encourage the use of existing research to guide further inquiry. But to focus only on those points of analytical similarity is to miss mining the full richness of spectral data sets. Spectral sensors also collect data for which *only* non-literal display is possible.

Even existing spectral analysis research does not provide a comprehensive picture of potential spectral data visualization research issues. Literature exists from the 1960s onward on the use of false color in MSI and on the utility of color vs. black and white or grayscale imagery. However, the literature primarily describes research that deals with far fewer bands, and therefore, describes much less complex visualization problems than those posed by ultraspectral sensors. Issues concerning the analysis of spectral data, which could be expressed quantitatively (graphically or numerically) or qualitatively (pictorially), are critical scientific visualization issues.

The complexity of the scientific visualization issue can be illustrated by several examples of hyperspectral analysis techniques. Figures 2 and 3 below offer examples of the strengths and weaknesses of false color imagery and spectrographic charts for hyperspectral data display. Figure 2 is the familiar Jet Propulsion Laboratory spectral data cube, derived from data acquired by the Jet Propulsion Lab's (JPL) Airborne Visible/Infrared Imaging Spectrometer (AVIRIS) in a 1992 National Aeronautics and Space Administration (NASA) ER-2 collection test flight. Taken over Moffett Field, California and showing the southern end of the San Francisco Bay, it displays pictorially the volume of date collected across all 224 of the AVIRIS spectral channels. The upper horizontal plane of the cube is false-colored to emphasize the water and evaporation pond structure visible on the right. Moffett Field airport is also visible on the left (JPL, 1994).

The sides of the cube are presented as slices and display the edges of the same image in 224 bands. The upper vertical plane of the sides falls in the visible part of the spectrum (400 nanometer-wavelengths), and the lower falls in the infrared (2,500 nanometers). The sides are false-colored to demonstrate the range of sensor response from low (black and blue) to high (red). In the upper right corner of the long edge (front) of the cube there is an area of high response in the red portion of the visible spectrum (about 700 nanometers) that indicates a concentration of 1 centimeter-long brine shrimp within the pond (Chovit, 1999). The cube shows locational relationships for components within the area of interest, but only provides approximations of individual components' spectral signatures and relative shifts in signature across the image.

Figure 3 shows the spectral graph for a single pixel within an AVIRIS return. The x-axis shows channel wavelength in microns. The y-axis shows radiance. The shape of an AVIRIS spectrum is affected by the light curve of the Sun and the absorption features of the atmosphere. Sun effects peak in the green wavelengths and diminish at higher and lower wavelengths. The components of the atmosphere (primarily nitrogen, oxygen, carbon dioxide, and water) absorb light at known wavelengths and their effects can be identified. For example, atmospheric water causes the deep valleys at 1.4 and 1.9 microns. Once sun and atmospheric effects have been identified (or algorithmically "corrected"), what remains is the pixel's spectral signature, corresponding to the chemical composition of the area being imaged (the size of the area varies with the resolution of the sensor). Every substance's spectral signature is unique. In the graph above, the presence of vegetation is indicated by a large peak where red light (0.7 microns) merges into the infrared (the chlorophyll in vegetation absorbs the visible light from the sun, but reflects infrared radiation (Chovit, 1999). Single pixel spectrographic presentations can identify components within an area of interest, but do not show locational relationships nor do they show frequency or density of occurrence within the image.

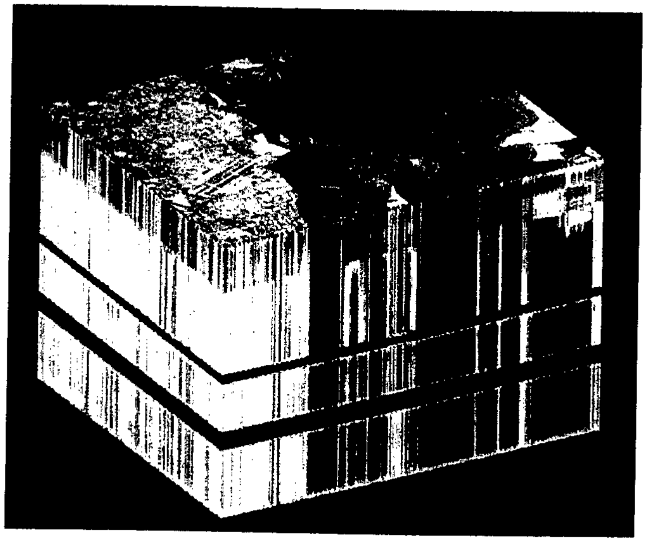

Figure 2. AVIRIS Moffett Field Image Cube (JPL, 1994).

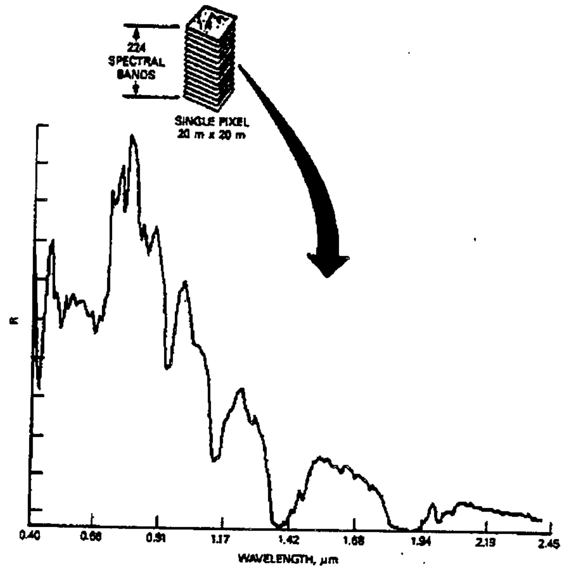

Figure 3. AVIRIS single pixel spectral display.

The examples above illustrate the difficulties of providing adequate support for the four disparate groups of military analysts who will exploit spectral data in future wartime scenarios. The adequacy of current spectral analysis techniques will vary relative to the varied task timeframes. Use of both graphical and pictorial displays, as done by NAIC and non-military HSI analysts, requires both time and training. Although some level of training will conceivably be offered to tactical intelligence professions, it cannot match the scientific background of NAIC specialists, while the time pressure under which tactical operators must work is irremediable. The warfighter will, of necessity, have the most limited training and the most constrained timeframe. The field utility of current hyperspectral analytical techniques is necessarily restricted to a few targeting scenarios. A further consideration for all users, time constraints imposed by current hyperspectral data analysis techniques—performed for hundreds of bands—make the task of displaying pixel data for an ultraspectral data cube's thousands of bands daunting, and it makes advances in fusion algorithm development (such as the distillation techniques discussed earlier) absolutely critical.

Existing spectral imaging collection and exploitation prototypes are not fully matured test beds. However, the Common Spectral MASINT Exploitation Capability (COSMEC) Workstation, a prototype development project funded jointly by the Central MASINT Office (CMO) and NAIC, provides an intelligence-oriented, ground-based, remote sensing analysis capability for both hyperspectral and multispectral data sets on a micro or minicomputer-based platform. COSMEC has automated import functions for Landsat and Hyperspectral Digital Imagery Collection Experiment (HYDICE) data cubes and a generic import function designed to support multiservice military sensor data cube formats. It operates in both UNIX™ and Windows NT™ environments and uses a standard Windows-type interface with keyboard and mouse inputs. COSMEC employs algorithms for atmospheric correction, pixel and sub-pixel classification, and target signature matching and provides supplemental exploitation capabilities through the inclusion of two commercial exploitation programs, ERDAS IMAGINE™ and ENVI™.

In 1998, the Air Force Research Laboratory's Human Effectiveness Directorate sponsored a preliminary human factors-oriented evaluation of the COSMEC display interface. The COSMEC evaluation identified a number of deficiencies with regard to both the automation of algorithms used with

HYDICE data and to workstation processing functionalities. Although the newest iteration of COSMEC (which has been distributed to national agencies for beta testing) has improved a number of the problem areas, comprehensive human factors testing of spectral display visualization techniques, analytical support, and product development remains to be done (Long, Robeson, Fitzhugh, Bradford, & Kuperman, 1999). Intuitive interfaces, informative displays, accessible support data, and advanced fusion algorithms are all requirements for effective near-real and real time exploitation.

The question of optimal method of presentation (whose answer will undoubtedly vary not only for user group to user group, but possibly from band to band) is both a human factors issue and a cognitive engineering issue: It relates not only to human perceptual and processing capabilities inquiry, but also to research in display interface design. Related design issues, such as how to speed information access, how to optimally order presentation of information, how to highlight time-critical information, and how to organize stored information to optimize retrieval strategies, are equally critical to successful spectral exploitation workstation design. While some applied research has been done in aspects of data access, data presentation, and data mining, existing results provide little more than indirect guidance. There will be no clear answer to how best to design displays for ultraspectral data tactical exploitation without pursuing scientific inquiry specifically using spectral data.

RESEARCH RESULTS

Vision and Perception

The literature search done in support of this study identified a serious lack of vision-based research supporting current spectral exploitation efforts. Current investigations focus primarily on the system rather than on the user. As is often the case, when system design overlooks human capabilities and human limitations, the "usability" of the design is likely to suffer. Although a great deal of basic research exists on the operation of individual components within the visual system and on functions within the perceptual process, much research remains to be done in order to complete our understanding of the complexities of human vision. Questions remain concerning how our vision capabilities affect our ability to use visual displays, and conversely, how visual displays may be designed to optimize visual response.

Applied research in visual performance, including visual search and target detection tasks, is also available, but advances in display technology outstrip our ability to define technology's impact on visually based tasks. Until now, imagery-based visual performance research has been done with respect to traditional visible and near visible spectrum imagery products, such as photographic, radar and infrared imagery. Some of the principles discovered in those investigations appear to apply equally to HSI/USI spatial data analysis. However, as noted earlier, spectrally generated spatial images offer different challenges than traditional imagery formats and the interpretative cues used in traditional imagery do not fully overlap those for spectral interpretation.

An abbreviated discussion of vision topics follows, including a brief examination of some of the known principles of visual perception affecting visual performance. It is followed by a representative set of image qualities and visual effects that are likely to become performance issues for spectral data-generated scene interpretation and for spectrally based visual search and target detection tasks. They are illustrated by spectral spatial image reproductions and indicate fruitful topics for future research regarding spatial exploitation of spectral data.

<u>Visual Psychophysics and the Visual System</u>

Psychophysics is the study of quantitative relations between psychological events (sensations) and physiological events (sensation-producing stimuli) and is concerned with accurate measurement, on a physical scale, of the magnitude (or intensity) of a stimulus. Applied psychophysics issues are the relationships among measurable sensory thresholds, sensory stimulus presentation, and task performance effects.

Visual psychophysics relates to image interpretation and target acquisition tasks through a network of vision-related factors. Both the visual capabilities of the analyst and the environmental conditions under which the analyst works affect analytical performance. The specific concerns of visual psychophysics include the definition of the thresholds of operations for the components of human vision. The quality of the visual system (and hence, visual performance) is dependent on:

1. Refraction Optics
2. Retinal Diffusion
3. Receptors Distribution
4. Accommodation
5. Involuntary Eye Movement

Each of these topics of vision research describes potential areas of variability in human visual performance. Normal ranges exist, and variations may be controlled in subject populations by administration of performance tests to identify candidates whose capabilities fall within the accepted range. However, the importance of considering the visual system's limitations cannot be overstressed, as reports in the literature on extended exposure to computer displays show problems with visual fatigue, diminished blink rate (which is also a sign of excessive workload), and consequent dry eye syndrome (which negatively impacts focusing ability) already affect work output and cause workers to lose work time (Yamada, 1998). There is no good reason, through overlooking important variables, to design displays that will decrease the analyst's working conditions, increase his/her discomfort and increase his/her workload.

The following table maps topics in vision research to specific visual qualities that may serve as visual performance discriminators. Working definitions are offered for each visual quality under consideration, and a brief discussion of human vision capacities as related to target search is provided. The information in Table 2 and in the vision subsections was compiled from several sources on visual perception (Goldstein, 1980; Gordon, 1997), visual psychophysics (Jameson & Hurvich, 1972; Kantowitz, Jameson, & Hurvich, 1972), and vision and acquisition (Overington, 1976).

Table 2. Vision Topics, Vision Qualities, and Related Visual Capabilities

Vision Topic/Quality	Visual Capability
Refraction Optics	
Acuity: Sharpness of pattern vision.	Subjects with 20/20 vision can see a line subtending less than 1 sec of arc, distinguish the difference in laterally displaced lines at 10 sec, the difference between arcs of different lengths at 12.4 sec, and between twin points of light at 0.15 mrad (or 30 sec).
Retinal Diffusion	
Contrast Sensitivity: Sharpness of spatial vision (contrast perception, edge detection).	Spatial frequency sensitivity is greatest at 4-5 cycles/degree of visual angle and falls off at both higher and lower frequencies. Subjects with less than 20/20 visual acuity have poorer spatial acuity as well, even with fully corrected vision.
Rod & Cone Distribution	
Color Vision: Trichromatic (red, green, blue) vision. **Rod Vision:** Peripheral vision, low light vision.	Combined ratios of responsiveness to stimuli provide color perception. Color vision is provided by 6M cone receptors in the fovea and peripheral retina. 120M rods in the periphery provide achromatic vision. The eye can distinguish approximately 200 shades of gray and 20,000 increments of color change. Rods in the extrafoveal area offer better vision at low ambient light levels. Peripheral vision cues foveal vision. In target search tasks, the eye scan pattern (a series of jumps and dwells equivalent in purpose and in frequency of occurrence to saccades and intersaccadic intervals) follows regions of visual interest. Target (or possible target) glimpses in the extrafoveal area cue the eye to fixate on the object in the next dwell.
Accommodation	
Focal Ability: Muscular movements adapting to different focal distances.	In normal vision, the focal distance for the eye at rest is around 0.8 m from the retina. Focal distances of a fraction of a meter through infinity can be obtained by adjustment of the ciliary muscles.
Involuntary Eye Movement	
Saccades, Tremor, Drift: Mechanisms that prevent muscular seizing and the fixation-induced loss of retinal image.	In *saccades*, the focal point changes 3 times per second, as the eye replaces the original retinal image with one displaced 1.5 mrad, and may be the eye's attempt to correct fixation point or to obtain multiple images in order to account for noise in the optical system. *Tremor* refers to the oscillation of eye muscles that maintains the eye's focus while keeping the muscles from seizing. *Intersaccadic drift* is a 0.7 to 0.9-mrad/second image drift across the retina, due to residual muscle imbalance. Eye movement is critical—stabilization causes loss of retinal image.

A number of external factors affect the performance of the vision system in visual search and target detection tasks. The speed at which presentations are made, conditions of presentation which require rapid changes in light adaptation and focal distance, and the position of presentations relative to the retina each impact individual visual performance. A brief list of human performance responses to visual presentation issues is offered below.

Temporal Presentation: In short duration (flash) presentations of up to 2 seconds, detection thresholds are inversely proportional to viewing time. As presentation time increases, detection thresholds stabilize.

Adaptation Time: The eye requires time to adapt to differences in field luminance before it can achieve optimum performance. Detection thresholds are negatively affected by inadequate adaptation.

Accommodation Time: The eye requires sufficient time to accommodate to changes in focal distance (optimally about .8 m from retina). In middle age, accommodation time increases. Detection thresholds are negatively affected by inadequate accommodation.

Retinal Position: In good light conditions, detection thresholds rise as object distance from the fovea increases. In poor light, detection thresholds lower for objects outside the foveal area.

Image Quality Factors

The quality of the image presented has a direct effect on analyst performance in visual detection tasks. Results for experiments examining the effects of changes in individual and combined factors indicate their importance in imagery analysis. While image qualities may be a function of data collection, and therefore, be considered engineering issues, some image qualities are inherent in the imaged scene. Knowing how image qualities such as contours, texture, and scene clutter, for instance, are perceived by the analyst ultimately provides insight into how to artificially enhance images for faster, more accurate interpretation.

The following table lists image quality factors and provides information on how each factor affects human performance. Each represents current topics in basic vision research, but also suggests manipulable variables for spectral presentation visual perception and visual search experiments. Little or no data has been collected on the effects of image quality factors on spectral scene analysis; all areas remain open to research.

Table 3 . Image Qualities and Related Visual Capabilities

Image Quality	Visual Capability
Brightness: Perception of light intensity	Visual performance is optimized for natural illumination. As field luminance decreases, detection thresholds rise. Foveal (cone) vision is used in high scene luminance. Rod vision, which is best peripherally and is achromatic, becomes more effective in low scene luminances.
Contrast: Perception of differences in intensity of two objects (target against field)	Lower field luminances require higher target luminance for detectability. Objects within scenes rarely show uniform luminance, which makes both contrast and contour detection tasks more difficult. Variations in luminances contribute to scene interactions.
Size: Size of target relative to other objects in scene	The eye can detect a black disc of 0.15 mrad (or 30 sec) angular subtense against a plain background in good light. As size increases, contrast thresholds decrease, but level off above 30-60 mrad in diameter.
Shape: Variation in shape of object viewed from different aspects	As object area increases, contrast thresholds decrease. Complex scenes are broken up into *geons* (small, simple geometric shapes) for visual processing. In both shape and contour detection, visual responses are very good for vertical edges, next best for horizontal edges, but significantly poorer for angular presentations (45° angles offer worst detection performance).

Image Quality	Visual Capability
Contours/Edges: Narrow regions that visually separate objects from field	As contour edges are blurred, thresholds for detection rise, with massive effects in small images and large effects in larger images. There are significantly smaller effects for blurring of very large objects. In contrast, blurring of narrow straight lines yields less performance degradation than for wider lines. The longer the presentation time, the more effect blur has on detection performance.
Clutter: Scene complexity; scene interactions	Complex scenes displaying multiple background/target interactions (visual interference) increase detection thresholds.
Texture: Small-scale luminance variations within objects and field	Small-scale luminance variations within scenes causing screen graininess (may be a product of sensor-processing), organized patterns produced by streets or cultivated fields, or characteristic visual effects produced by fiber optics may help or hinder detection, depending on whether they are classed as random noise or as "intelligence." Random variations that affect target and scene equally raise detection thresholds.
Color: Use of hue and saturation to differentiate scene elements	Effects for color contrast are similar to monochromatic luminance contrasts. Standard false color composites in spectral imagery (Landsat), which use red for infrared and blue and green for the visible spectrum's green and red bands respectively, produce images that are primarily red and blue—the hues which provide the least visual detail and induce visual fatigue. Use of yellow and green hues increases sensitivity to imagery detail.

Environmental Factors

Performance in visual detection tasks relies on environmental variables as well. Environmental conditions may or may not be controllable, as environmental control itself may vary with situations. However, knowledge of how environmental factors affect analyst performance permits (and encourages) the design of equipment for optimum performance. A short list of environmental factors follows.

Viewing Conditions: Less than optimum viewing conditions (e.g., ambient light) impact performance negatively. Visual performance is maximized for natural lighting. Detailed visual discrimination tasks require as close an approximation of natural lighting conditions as possible.

Display Equipment Limitations: Equipment limitations include both display resolution and color capabilities. Increasing resolution and color capability offer positive impacts on performance.

Sensor-Provided Image Quality: Sensor limitations may include image noise (atmospheric effects, such as fog, rain, ice), image blur (effects of atmospheric scattering or signal strength), and image resolution (level of detail provided by sensor "sensitivity"). Image noise and blur have negative effects on detectability thresholds.

Visual Issues in Spectral Scene Analysis

Visual Effects

Spectral data-based imagery may be considered an embedded visual display. In embedded displays, targets are overlapped or occluded by other scene elements (Carmody, Scanlon, & Dasaro, 1990). Background context influences fixation duration, saccadic intervals, peripheral detection and foveal refixation in target detection tasks. Embedded searches call for different search strategies than non-embedded displays, such as increased visual attention, involving more comparison scans (between suspected target images) and more clustered fixations (fixations within an identifiable radius).

Edge detection and contour detection are important context clues, as are shading and texture. In most cases, straight lines indicate manmade scene elements, and depending on the regularity of the contour, contoured elements may also indicate non-naturally occurring scene elements. Contour within an image may refer to either overlapping (proximity principle of visual organization) or similarly oriented elements (similarity principle) that are perceptually processed as forming a single larger visual element (Braun, 1999). Figure 4 (below left) provides a simple example of visual contour encountered in a larger scene. While in this case, the perception of circular images is valid, in true embedded scenes, visual organization of scene elements by perceived contours may enhance or impede scene interpretation. In imagery, terrain character may be deduced through contours. In Figures 6 and 7 on the following page, the repeated, contiguous, wavy lines indicate terrain contours, but due to luminance contrast, also are perceived as edges.

Edges are detected through differences in scene element luminance distribution. While edge detection may be very useful in interpretation of scene elements, the luminance differences may produce interference effects. Sharp changes in luminance gradient may cause the Mach band phenomenon. Mach bands are false brightness gradients displayed at the boundaries of two adjacent scene elements (a distinct area of lightness between two areas of differing darkness; a distinct area of darkness between two differing areas of lightness). Perception of Mach bands (view Figure 5, below right) can inhibit or otherwise influence scene interpretation.

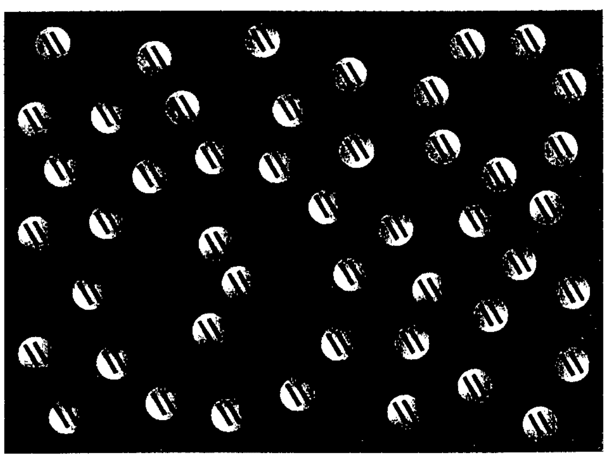

Figure 4. Two circular visual contours formed by proximity-grouped figures.

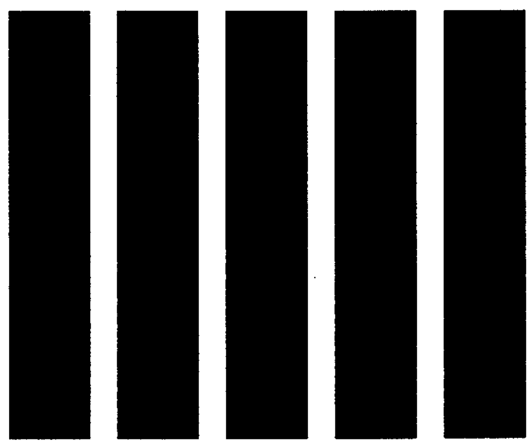

Figure 5. Mach bands visible at the edge of dark and light bars.

Visual contours, discussed above, provide edges of contrasting luminance and are subject to the same visual phenomena as the straight lines shown above. Figures 6 and 7 on the following page are AVIRIS hyperspectral-generated images of terrain in the foothills of Virginia's Appalachian Mountains showing agricultural activity (JPL, 1999). Both terrain contours and agriculturally created contours illustrate real-world edge detection tasks, with associated Mach band phenomena. (The contour effects may, however, have been artificially enhanced by what appear to be JPL-initiated data loading errors inherent in the captured images.)

Within imagery, shading is an interpretive cue for changes in substance (reflectance), structure (shape) and illumination (shadow). The nervous system multiplexes the signals and passes them on the cortex where they are unscrambled (Kingdom & Mullen, 1995). Shading indicates three-dimensionality, suggesting cylinders and cubes and cones through the apparent fall of light on the object.

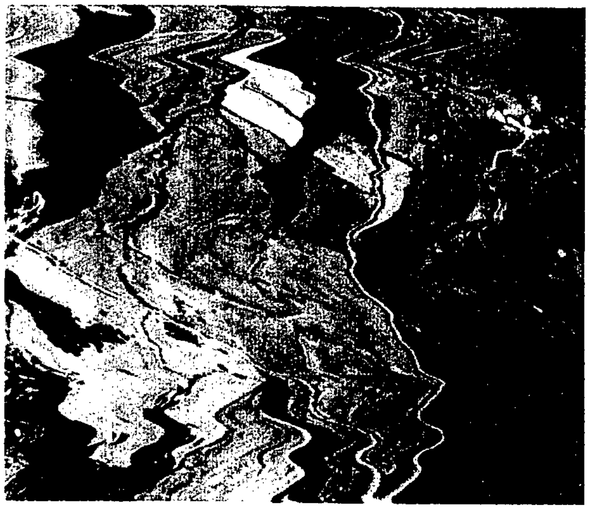

Figure 6. AVIRIS image showing Leesburg, VA.

Figure 7. AVIRIS image showing HyHill, VA.

Texture also serves as an interpretative cue. Perceived surface textures are due to apparent albedo (the fraction of light reflected by a body or a surface) and chromatic variations or by surface roughness (small shading variations that appear to be three-dimensional). Perceived shapes within the image are referred to as geons, the simplest shapes recognized by the brain as discrete scene elements. Apparent texture provides distortions, gradients, and discontinuities relating to the position, orientation, and shape of the object; it displays the visible properties of the object's material composition. Texture also can be considered an abstract optical design, layered onto the other visual designs that characterize the object. Texture may shift with the shifting shape, orientation or position of the object, as light and shadow and aspect angle change its appearance, or it may remain stable. For some alterations, such as shape changes due to edge damage, the texture is independent of object shape. For example, a torn edge has the same texture no matter what the shape of the edge may be (Pickett, 1968).

Recent research in perceptual processing of contours indicates that figure-figure segregation (the differentiation of two adjacent figures which appear equally visually important), may not occur in the pre-attentive state, as once thought. Rather, it is a function of object based attention, and as such, costs the analyst in both processing time and diversion of attentional assets (Roelfsema, Scholte, & Henke, 1999). Visual analysis of a scene may necessarily involve terrain contours, and while the task may not overtax a national, theater, or tactical analyst, close inspection of contoured terrain within imbedded scenes may unnecessarily burden a warfighter in time critical targeting scenarios. Comparisons of warfighter performance in ultraspectral target detection tasks of varying levels of complexity may provide a useful measure of the effects of spectral data presentations on warfighter target detection.

The figure/ground visual effect is another processing phenomenon that may affect interpretation of visual scenes. In figure-ground segregation, unlike figure-figure segregation, the figure initially appears to have more visual importance than the perceived background (ground). However, a refocus of attention causes a reassessment of relative scene element importance and transforms the background into the more important visual element. An unusual example of a classic figure/ground illustration is the shown in Figure 8, on the following page; the two facial profiles form a positive space within the image, while the negative space, if focused upon, takes on the shape of a vase.

Figure 9 illustrates the figure/ground effect within a monochromatic hyperspectral image (JPL, 1998). Focus on the light areas within the scene leads to a somewhat different visual interpretation than focus on the dark areas. If one is unaware or unsure of the spectral significance of the shading, which areas are foreground, and which are background? What do the lighter areas signify? What compositional element is being displayed? The novice or time-constrained analyst might be unprepared or unable to crosscheck visual interpretation against spectrographic data. While it is true that an experienced analyst is not likely to encounter the degree of uncertainty described, if spectral-based data is made available at the unit level, some confusion between the properties of processed spectral imagery and photographic imagery is not beyond reasonable expectation.

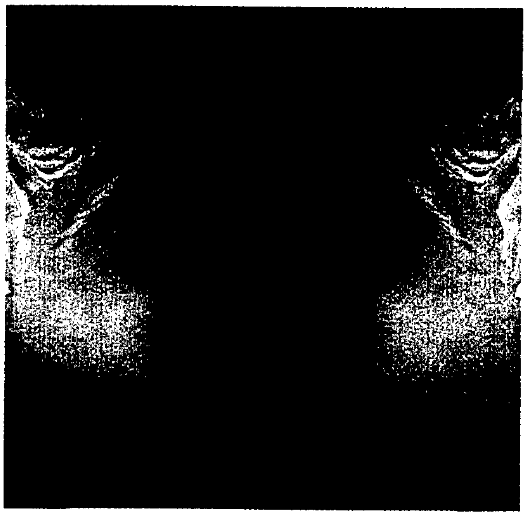

Figure 8. Face to Face by S. K. Webster. http://www.psych.westminster.edu/ceramics/self.html

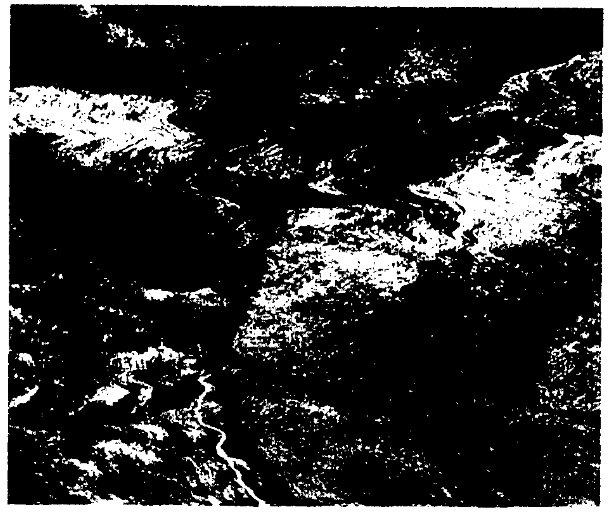

Figure 9. AVIRIS monochromatic image of Bartlett Experimental Forest, NH.

Color in Spectral Data-Based Imagery

The use of color is an important issue in visual scene analysis. There are several approaches to the consideration of color utilization. One approach is to look at true color imagery as compared to false color imagery. True color may or may not adequately represent the level of detail necessary to interpret the image. In false color imagery, the color may represent different values. In some cases red, blue, and green are used to signify their respective positions on the spectrum; in others they are arbitrarily assigned to specific bands in order to enhance visualization of the distribution of components within a scene. Figure 10, on the following page, compares a true color composite image to a false-colored shortwave infrared composite. It is clear that the true color image is unable to show the level of detail that is brought out in the false-color composite.

Assignment of red, blue and green values to specific bands is a standard technique to enhance interpretability. The set of images in Figure 11, also on the following page, is taken from the *Multispectral Image Interpretability Rating Scale (MS IIRS) Reference Guide (Annex B in SITAC's Multispectral Users Guide)*, as is the text that follows it. The MS IIRS, a seven-level scale derived primarily from the DoD *MSI Requirements Survey*, as well as inputs from interested civilian government agencies, consists of an escalating set of criteria (typical exploitation tasks) that indicate the level of detail discernible in the image. Produced in 1995 by the Image Resolution and Reporting Standards Committee (IRARS), it is not a sanctioned rating scale but offers a baseline for spectral image interpretability rating and also presents information on existing sources of multispectral imagery and multispectral image applications.

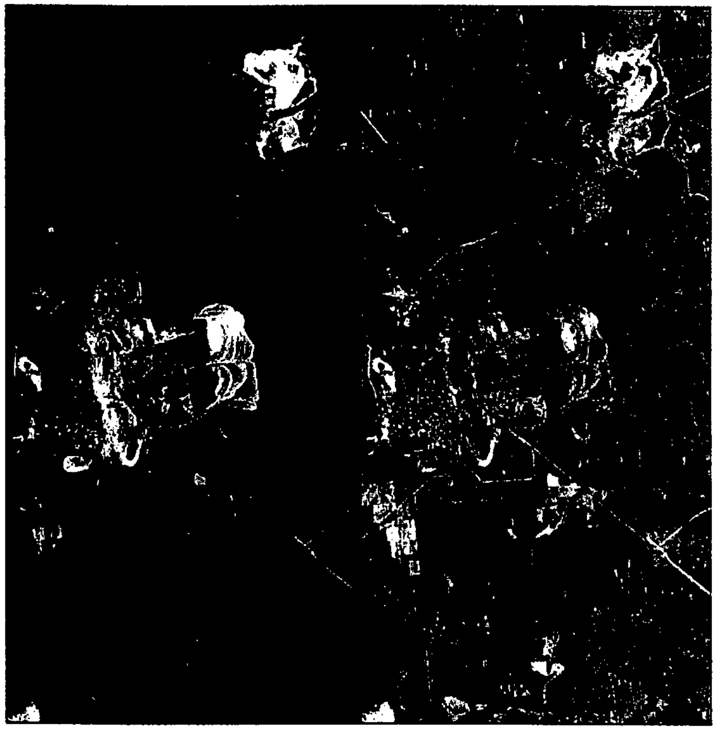

Figure 10. July 4, 1989 Landsat Thematic Mapper (TM) images. True color composite (left); Shortwave infrared composite (right). From the *MS IIRS Reference Guide.*

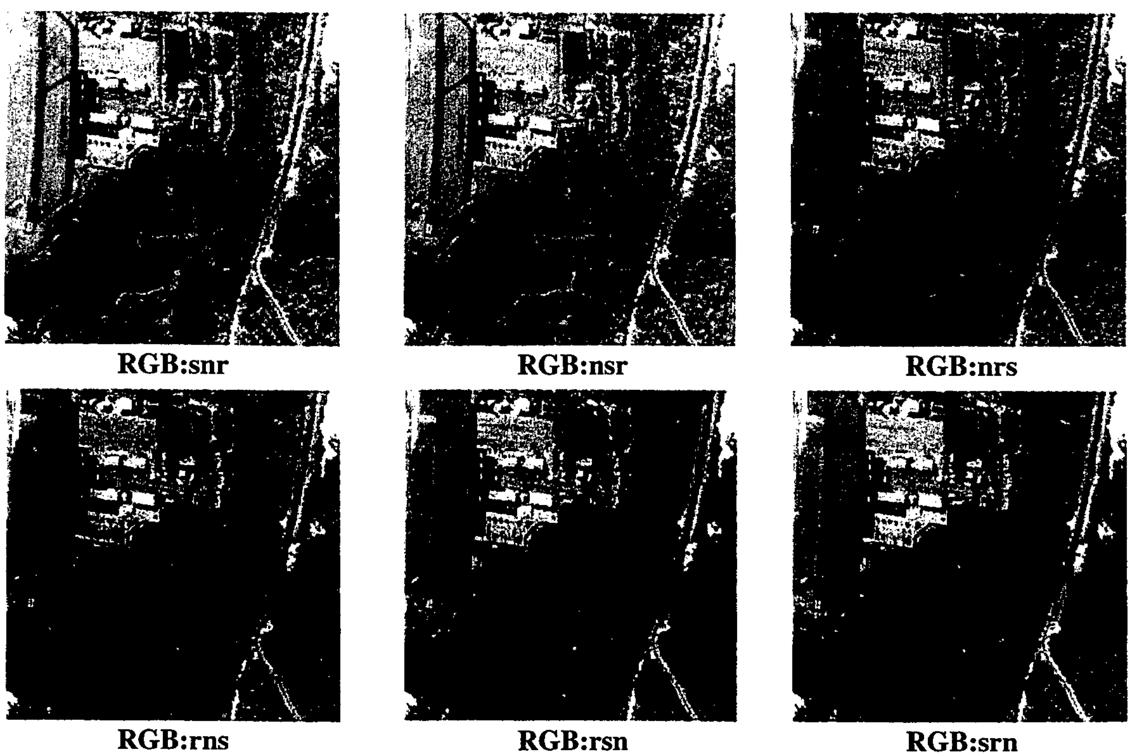

Figure 11. Composite options for three spectral bands: red (r), near infrared (n), and shortwave infrared (s). From the *MS IIRS Reference Guide.*

Once the preferred bands for maximizing spectral contrast have been selected, the color display presentation does not significantly influence interpretability. As illustrated…, if a feature/background contrast exists, it will be apparent in all presentations using those bands even though there may be a subjective preference for one presentation over another. For example, while the colors differ in all six permutations of the three-band composite shown in this figure, the large buildings can be spectrally distinguished from the trees, reservoir, or concrete in any of them. The concrete, however, is not very different spectrally from the dried grass in any of these bands. Therefore, the color of these two features is similar in all six representations (*MS IIRS Reference Guide,* 1995).

The color-coding schemes shown on the previous page *are* relatively benign, although there actually is a noticeable difference in level of detail between the first two images (top) and the last two (bottom). However, consideration should be given to other uses of false color that actually violate psychophysical and color theory principles. The human visual system is more sensitive to yellow-green than to red-blue hue combinations. Blues and reds must actually be brighter than greens and yellows to be perceived as being of equal brightness (Landay, 1998; Jameson, 1972). The eye's photopigments are not distributed evenly throughout the eye; 64 percent are red, while only four percent are blue. The center of the foveal area has no blue cones, which explains the eye's relative insensitivity to short wavelengths and its relative difficulty with blue edges and shapes (Landay, 1998). Juxtaposition of concentrations of red and blue hues lessens the perceptible visual detail (Richards, 1986) and search tasks that require close inspection of adjacent areas of red and blue induce visual fatigue (Helander, 1987). Highly saturated blues and reds together produce chromostereopsis (short wavelengths are refracted slightly more than long wavelengths, creating a positional disparity on the retina), in which the eye interprets the wavelength differences as differences in depth (Rice, 1991). The following pair of images illustrates the necessity for care in selection of colors.

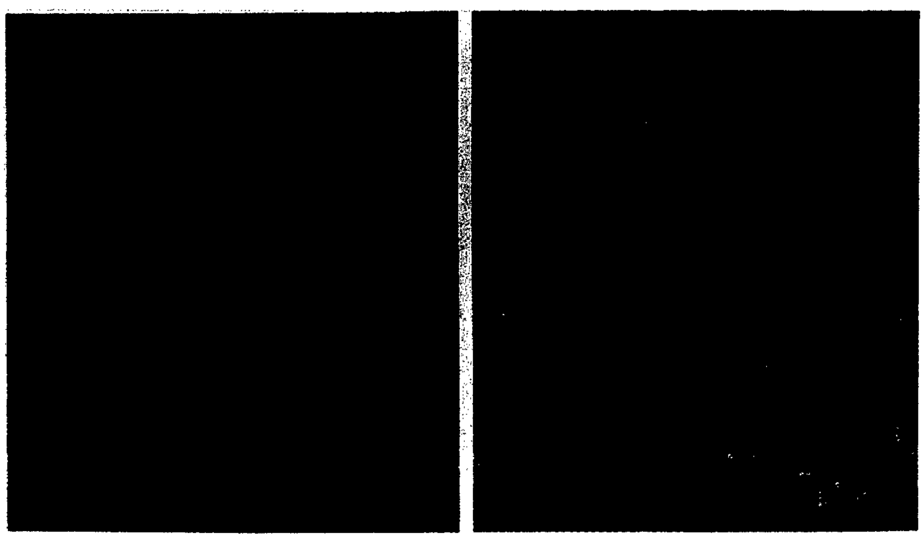

Figure 12. Landsat multispectral scanner false color composites; left shows standard color assignment, right shows bands 7-5-4 as grb. From Richards, 1986.

Furthermore, the assignment of color by spectral band is, of necessity, limited to the three phosphors of the visual display terminal (red, green, blue) and becomes therefore, a bottleneck that permits the display of only three bands worth of data at a time (Richards, 1986). Without fusion algorithms, it is difficult to see how full exploitation of hyperspectral or ultraspectral data sets could be speedily accomplished. Assignment of in-pixel target signature characteristics to three colors, redrawing the spectral scene, and interpretation—repeated for in three bands sets across the all available spectra and reviewed simultaneously or in sequence for comparative analysis—is, and can only be, time-consuming. Application of algorithms, which correct atmospheric attenuation and absorption phenomena and categorize and quantify pixel and sub-pixel spectral data characteristics for pictorial coding, can assist in breaking the bottleneck, but to make real headway against the level of data present in multiple spectral bands it is necessary to quickly identify and filter out irrelevant information and to fuse related information.

In scenes where multiple substances are being mapped, a color may be arbitrarily assigned to each component of interest. Several issues exist for color-coding: simultaneous contrast, color constancy, and stimulus-response compatibility are just three examples. The following spectral image in Figure 13 is a mineral map derived from an AVIRIS collection flight, in which each color displays the identification of specific minerals through imaging spectroscopy analysis (USGS, 1995c). In Figure 14, note how color contrast affects perception of the two inner boxes; they are actually the same color, although one appears lighter. In Figure 13, note the color perception difficulties presented by the proximity of the two shades of cyan with the bright blue and dark blue values. Also note the occasional difficulty distinguishing cyan shading from dark to light. As observed above, not all color combinations work equally well.

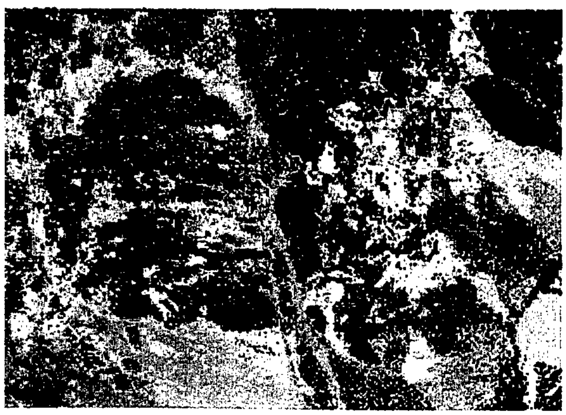

Figure 13. Mineral map from the USGS Spectroscopy Lab archives.

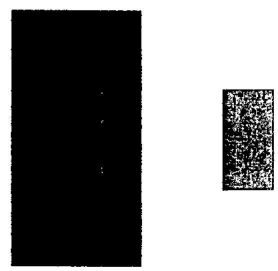

Figure 14. Simultaneous contrast; the surrounding color affects the inner color.

There are several reasons why, in spite of its ability to perceive thousands of increments of color change and to accurately match colors, the human visual system may not be accurate in its interpretation of color on video display terminals. Isoluminant stimuli of dissimilar colors differ in apparent brightness, or luminance, relative to their respective saturations: perceived brightness increases with increased saturation. The phenomenon is particularly notable for colors at spectral extremes, such as red and blue, but is relatively weak for mid-spectral colors (Stalmeier & de Weert, 1994). Red is a particularly problematic with respect to saturation and luminance, providing more intense stimulus than commensurate stimuli from other wavelengths because of the excitation effect of the contrast stimulus on the medium and long wavelength cones (Wachtler & Wehrhahn, 1996). Experimental inquiry has demonstrated that when both the illuminant and the surfaces within the scene are distinctive, surface matching through perceptual feedback ceases to be possible (Bäuml, 1999).

Color constancy describes the phenomenon under which an image displaying shading is perceived as being the same color throughout. The shadowed area may be slightly darker, and the illuminated portion may be lighter, but when viewed as planes on a single figure, they are processed as being uniform, displaying the variation normally expected from real lighting effects on three-dimensional objects. The expectation implied by the color constancy phenomenon can be problematic if the color mapping of shapes fails to apply the principle.

While color is obviously a useful tool in some interpretive situations, not all analysts prefer it for all analytical tasks. At NAIC, spectral scientists typically view black and white rather than false color spectral presentations for visual search tasks. Black and white displays provide excellent detail and often have emergent visual qualities. The introduction of color to characterize pixel contents may be of value—or it may introduce visual distractions that interfere with interpretation of the scene. However NASA and the United States Geological Survey (USGS) typically *do* include the use of false color imagery in spectral analysis to define areas of spectral similarity. Terrain characterization, land use, mineral and other natural resource distribution, and vegetation distribution and change are often determined using false color imagery to highlight the area or object of interest. While specific search tasks may recommend the use of black and white visualizations over false color, some of NAIC's analytical tasks are sufficiently similar to NASA and USGS work to make the question of chromatic preference worthy of further study. The level of coding in USGS maps requires unconstrained time and attention for processing, however, and while the level of detail may well be of value to the national analyst, it may be both unwieldy and unnecessary for the tactical analyst, whose interest is likely to be sharply focused. Figures 15 and 16, taken from the USGS web site, demonstrate the differing pictorial qualities of two types of images (USGS, 1995a&b).

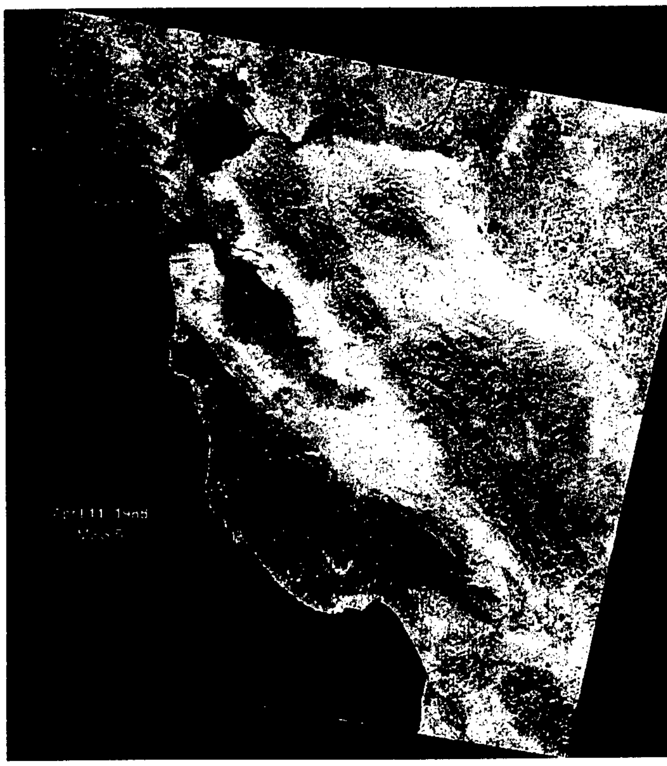

Figure 15. USGS black and white image (band 5) of the San Francisco Bay area.

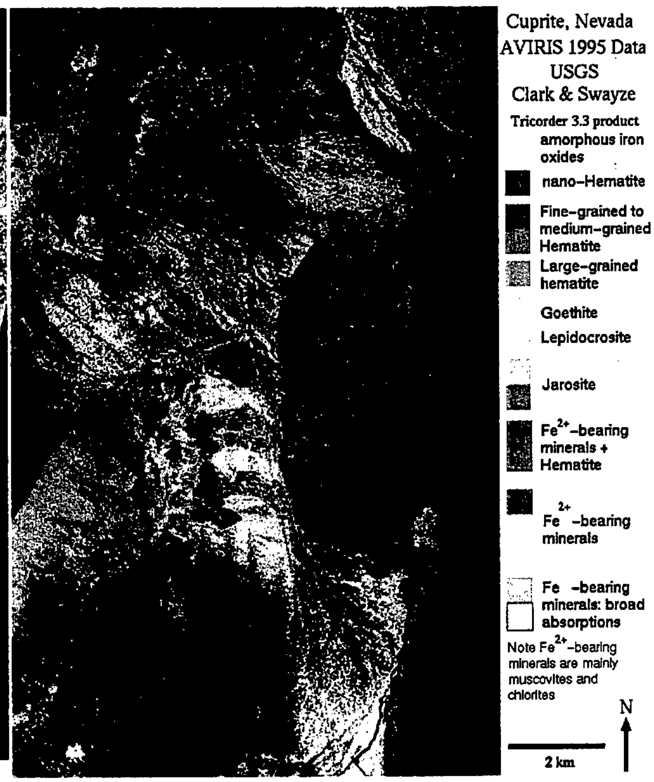

Figure 16. USGS false color map example.

The importance of color to visual perception, and hence scene analysis, cannot be overemphasized. The human visual system perceives 20,000 levels of color change. Our visual processing ability is based, in part, on the variation of sensation provided by the ratios of conic response to short (blue), medium (green), and long (red) wavelengths. The ability to distinguish so many colors is not without cost in attentional resources. Processing saturated (pure) hues requires more focus than desaturated colors (hue plus achromatic color). Different wavelengths of light have different focal distances: combinations of colors require constant refocusing and contribute to visual fatigue (Landay, 1998). Too many colors produce a visually confusing display; coding schemes should be limited to combinations of four or five colors if possible, for maximum interpretability of scene elements (Maguire, 1999).

Color familiarity—color in association with an object—provides a strong recognition cue. Color familiarity is a facet of stimulus-response compatibility (SRC), the human factors design principle that an interface that applies a "natural" systematic mapping from stimulus to response minimizes response times and errors. In developing SRC designs, empirical data shows the quality of the mapping rules to be secondary to the scope and number. Two basic principles apply to the development of mapping rules: 1) the fewer and simpler the mapping rules, the better and 2) mapping rules should be easy to learn, remember, and apply (Payne, 1995). The use of color familiarity as a guide for color mapping spatial data visualizations is consistent with simple, memorable mapping rules. The algorithmic assignment of realistic colors in target detection and other interpretive tasks may cue analyst attention to potential targets or objects of interest and enhance analytical performance. Conversely, the assignment of unrealistic colors may increase processing time and effort and may contribute to erroneous analyses. The following simple photographic example effectively demonstrates the interpretative value of color familiarity.

Figure 17, also from the *Multispectral User's Guide,* shows two series of images. The top series shows incrementally sharpened black and white photographs. The first photograph is very blurry and requires considerable attention to interpret, while the last, though sharper and more interpretable, still requires focused effort. The images shown in the color photographs below are much easier (and faster) to discern than their black and white counterparts.

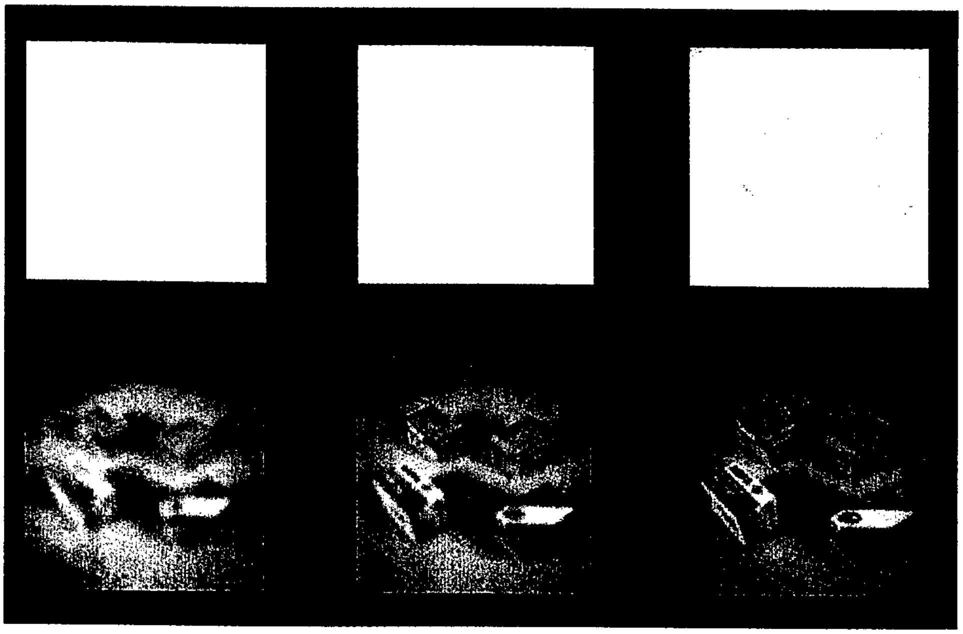

Figure 17. Color cues in object recognition.

The importance of color to visual scene interpretation cannot be overstressed. In false colored or color-coded spectral scenes, color assignment can make the difference between correct and erroneous interpretation and can speed or impede task completion. In intensive interpretation jobs, suboptimal color assignment can induce visual fatigue and contribute to inaccurate analyses. Conversely, the best performance results in visual search tasks have been obtained with color-coding. The effective use of color in displays has been shown to enhance performance and reduce eyestrain and fatigue (Pastoor, 1990).

Image Quality Effects

Image quality is as important to spectral imagery interpretation as it is to traditional photointerpretation tasks. The two multispectral images in Figures 18 and 19, taken from the *MS IIRS Reference Guide*, represent the same spatial resolution (GSD), but different levels of interpretability. Interpretability is based on sharpness, noise, and contrast, which may result from system parameters, acquisition conditions, and exploitation conditions. The first image displays high contrast and low noise; the second, low contrast and high noise. Noise may be caused by atmospheric attenuation (spectral scattering) or absorption (water in atmosphere).

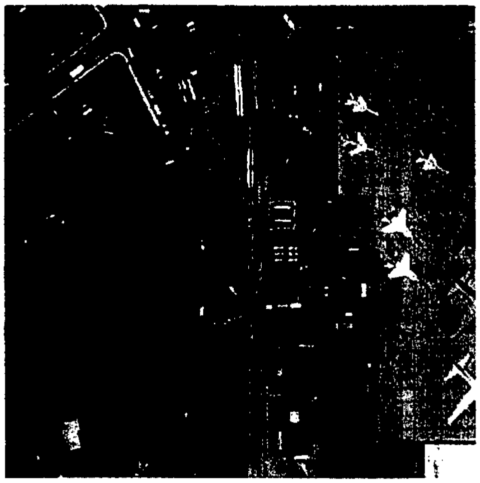

Figure 18. High contrast, low noise.

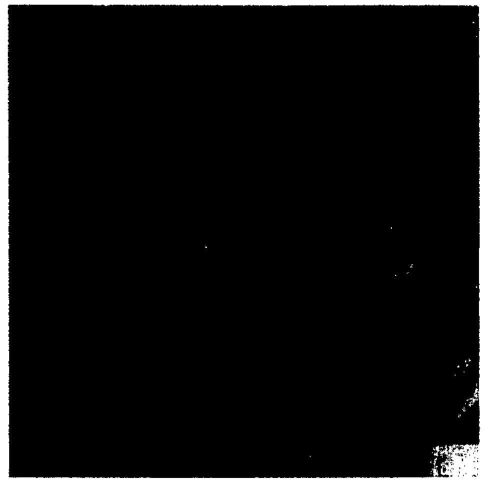

Figure 19. Low contrast, high noise.

The *MS IIR*'s ascending seven-level scale for image interpretability considers all bands of the image as a unit: spectral bands are intended to be used together, rather than viewed as separate images. The single rating given to a spectral image ranges in quality from ability to distinguish between land use (urban vs. rural) and terrain characterization (delineation of shorelines, identification of wetlands), to ability to detect paints and detect livestock and wildlife, to ability to distinguish between actual objects and decoys, distinguish between crop rows, and detect large holes by identification of the loose soil rings around them. USI promises the ability to interpret an even greater level of detail, including the identification of effluents and the outgassing of metals, increasing positive target identification confidence.

The difficulty of target detection tasks in imagery collected for military use may vary, as the imagery may vary considerably in its quality. In operational settings, second opportunities to make up for equipment failure, weather effects and hostile interference are rare. Airborne sensors, in particular, because of their tactical role, may be subject to circumstances that degrade collected sensor data. Even spaceborne sensors may be influenced by atmospheric effects in battle areas. Methods must be developed to exploit "atmospherically corrected" spectral data to support rapid response spatial imagery analysis.

In-Scene Target Coding

Traditional visual search tasks have benefited from judicious use of coding schemes. Academic research has focused on which coding schemes are most beneficial in simple search tasks. Most research has involved letter or figure searches among sets of letters or figures; little academic work has been done specifically with in-scene coding in embedded search tasks. Military efforts have involved the design of automatic target recognizer/classifier systems for aided interpretation of military imagery in targeting scenarios and provide a limited amount of data. The strategies pursued for visual search tasks vary in applicability to spectral imagery interpretation. Within the limitations of its original context, research has found that increased luminance of potential targets, color codes, and flashing effects, applied singly, can highlight areas of interest without obscuring other scene elements or destroying the visual context. Empirical evidence shows that redundant coding (more than one coding scheme) decreases search time and increases accuracy even more than single coding schemes (Van Orden, Divita, & Shim, 1993).

Choice of target color in a colored scene is important to successful searches. In experiments performed at Wright State University in 1992, researchers Nagy and Sanchez found that as target color difference (vs. distractor color) increased, search time decreased—up to a point (*critical color difference*)—and then response times leveled off. However, smaller differences yield stronger results, depending on the color combinations, while for some color combinations, search times could not be significantly decreased. The size of the stimuli in the display field was also found to be a factor, with small stimuli against a large display field showing large critical color differences (Nagy & Sanchez, 1992). While it is possible to distinguish colors with a difference above 6 CIELUV units (Neumann, 1998), between target and distractor, the least difference required for fast, effortless, searches is 20 CIELUV units (Carter, 1989). Luminance of targets was found useful only if the target was significantly brighter than the distractors. When the target was dimmer than distractors, there was measurable advantage to combining luminance and color. If the target was brighter than the distractors, adding color yielded no benefit.

Other coding schemes, such as boxes around potential targets and superimposed icons are problematic in complex scenes. Boxes draw attention to potential targets, but obscure context clues. Figure 20 below shows a one-meter resolution image of Washington, DC, collected by Space Imaging's IKONOS satellite on Sept. 30, 1999, using boxes to highlight "targets" (Space Imaging, 1999). The boxes indicate areas of interest (in this case, national monuments), which may be enlarged by the viewer. The interference with scene interpretation is clear, as the boxes obscure and hinder visual inspection of the contextual scene (however, the zoom capability is, in itself, very useful). In several recent aided target detection studies conducted at Wright-Patterson AFB, subjects identified a preference for "show/hide" cueing aids. Often the subject's strategy was to use the cueing box for initial identification and then to turn it off to better see the object of interest in its scene context (Riegler, Janson, Stewart, Fitzhugh, & Kuperman, 1998).

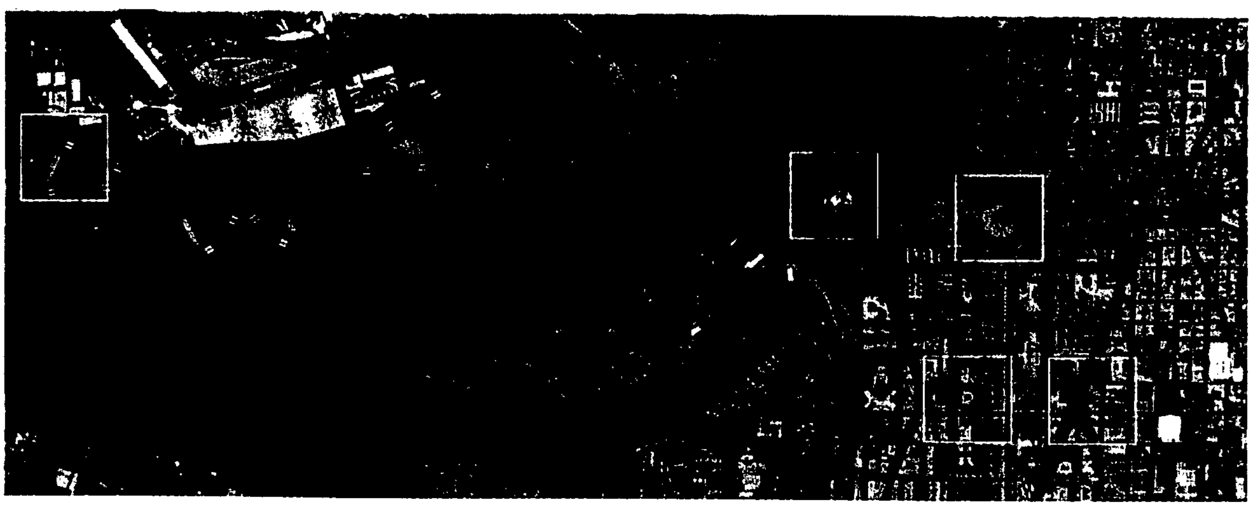

Figure 20. IKONOS satellite image of Washington, DC, showing boxes around objects of interest.

Superimposed icons (pictorial symbols) pose the same difficulties, in that they obscure contextual information and add to the effort required for interpretation. Basic icon recognition studies show that simple pictorial symbols require the least processing; that is, a simple tank silhouette is easier to identify than either a detailed line drawing of a tank (too much detail) or an arbitrarily assigned geometric shape (low stimulus/response compatibility). Well-chosen symbols are understood faster than text (Maguire, 1999; Wolff & Wogalter, 1998). However, as icons clutter a complex scene, they should be able to be turned off once attention is cued to the object of interest. NASA tests of superimposed symbology in heads-up displays and helmet-mounted displays shows that although the symbols convey the desired information, they also increase visual processing time and serve as distractors from other (far field of view) tasks (McCann & Foyle, 1994).

Confidence ratings for identification of scene elements may be indicated by color-coding, numerical ratings, and luminance cues. Target confidence ratings may be considered analogous to risk warnings, soliciting differing levels of attention. Color has long been used to indicate risk levels. Warning colors often follow the traffic light paradigm (i.e., red = stop, yellow = caution, and green = safe); the most familiar association requires the least interpretive processing. The American National Standards Institute (ANSI) standard uses red to indicate danger, orange for warning and yellow for caution. Another scheme moves from warm colors (red, orange, yellow) to cool colors (blue, green, cyan) to distinguish levels of importance; *Common Warfighting Symbology, MIL STD 2525B*, denotes decreasing levels of risk with red for hostiles, yellow for unknowns, green for neutrals, and blue for friendlies. However, in multiple studies, empirical data on comprehension of color warnings supports none of the schema above. The only consensus found among respondents is the acceptance of red to signal risk (Leonard, 1999). For exploitation system designers, the complexity of the data dictates the need to keep confidence rating coding schemes simple. Further, based on research findings, no common understanding of color warnings should be assumed. Any color-coding scheme should be accompanied by a reference key.

Confidence ratings may be indicated by numerical ratings superimposed on the scene. While numerical ratings are easily understood, they do add clutter to complex scenes. Luminance cues appear as promising for confidence ratings as they are for target cueing. No data was found on the superimposition of numerical, luminance or iconic cues on spectral imagery. While conclusions might be drawn based on cue utilization with photographic or other imagery, there was not a great deal of direct empirical evidence found by the researchers. The supplemental analysis of pixel or scene-level spectral data may render such cues unnecessary for the spectral scientist. However, the use of spectral imagery for tactical support may well develop a need to pursue experimentation in this area.

Levels of Target Acquisition

The task of target acquisition varies in complexity with the complexity of target shape and the complexity of the scene in which the target is imbedded. Thresholds for visual effects can be ascertained with respect to three levels of target acquisition.

Detection: Awareness of a localized energy signature (stimulus).

Recognition/Classification: Detection of characteristic structures or movements associated with a pre-defined category.

Identification: Recognition of individual features or behaviors associated with specific members of a category.

Both in target detection, and in the larger task of photointerpretation, the analyst uses automated decision aids. Design of spectral exploitation systems already includes processing algorithms, some of which correct for solar radiation and atmospheric influences and some of which provide varying levels of characterization of spectral returns on a pixel-by-pixel basis. Refinement of existing algorithms and development of new fusion methods may be expected to be incorporated into future exploitation system designs. However, algorithmic support alone cannot be expected to provide complete and unimpeachable data interpretation. Machine analytical capabilities and human interpretive capacity are not completely analogous. The following comparison in Figure 21 notes some of the relative visually related strengths and weaknesses of the human-computer system. Careful consideration of these analytical complements must be included in future workstation development efforts to make best use of both sides of the human-system interface.

Photointerpretation (by a human analyst)	Quantitative Analysis (by a computer)
Interprets on a large scale, relative to pixel size	Analyzes at a pixel level
Makes inaccurate area estimates	Can (may) make accurate area estimates
Can do only limited multispectral analysis	Can perform true multispectral (multidimensional) analysis
Can assimilate only a limited number of distinct brightness levels (approx. 16 levels in each feature)	Can make quantitative use of all available brightness levels in all features
Determines shapes easily	Determines shapes only through complex software decisions
Uses spatial information in a qualitative sense easily	Has limited techniques available for making use of spatial data

Adapted from Richard's *Remote Sensing Digital Image Analysis: An Introduction*, p.70 (1986).

Figure 21. Comparison of Human and Computer Interpretation Capabilities.

Spectral Analysis by Feature Extraction

Both civilian and military spectral analysts use algorithm-supported feature analysis to exploit spectral data. In the following three pages, an example is given of the sequence of analyst activity in typical exploitation tasks. Taken from an analytical example created by Dr. David Landgrebe of Purdue University and adapted from work displayed within the Electrical and Computer Engineering School's Multispectral Image Processing Laboratory web pages, it describes the analytical sequence, timeline, and spectral product of an urban scene data exploitation, using an analytical toolset developed at Purdue University. It also proffers an explanation of the exploitation process as a whole, which is included to provide useful background information.

Urban Scene Analysis

Researchers at Purdue University have been working on simplification of the spectral data analysis problem, reducing the costs in required bandwidth downlinks, and decreasing analytical time and rigor. Spatial resolution of spaceborne sensors is a limiting factor—the higher the spatial resolution, the more data produced, but the heavier the sensor, and thus, more costly the payload. The concept of using spectral measurements at the pixel level to determine ground composition was favored over traditional image processing techniques because it provided a faster, cheaper way to exploit spectral data. While target signature matching, discussed earlier, provides a means of training the algorithms to classify pixel contents, the requirement for large libraries of sample signatures (from different aspect angles, in different weathers, and at different seasons) makes sole reliance on signature matching analytical methods a daunting (and expensive) prospect. The premise of the analytic process is that algorithmic processing can simplify the analytical task if guided by the discernment of the human analyst. The human-aided machine system provides the interpretive power to filter the pixel-level multiband data down to a manageable level. A short discussion of the basis for the analytic process, feature extraction, will be followed by an annotated example of a typical analysis.

Spectral imaging provides a synoptic view of earth activities. The data collected by earth imaging sensors forms the basis for both spatial imagery (pictorial) and spectral data (pixel content classification). Processing and analyzing spectral data requires the combined efforts of computer processing programs and human analysts. While the objective, quantitative capability of the computer simplifies the enormous job of processing multiband data, the perceptive, associative power of the human analyst, and his/her ability to abstract and generalize is necessary to guide processing and interpretation. The figure below, adapted from *Information Processing for Remote Sensing*, provides a conceptualization of system relationships and the analytic process. In this representation, the system has three parts:

1. The scene (earth, sun and atmosphere), which cannot be controlled, and is both complex and dynamic.

2. The sensor, designed to provide data to the analyst, but not under control of the analyst while gathering data. The analyst has no choice in the spatial and spectral resolution provided and usually has no choice over the scene, time or season of collection.

3. The exploitation tool, which provides the analyst with control over processing algorithms and analytical strategies.

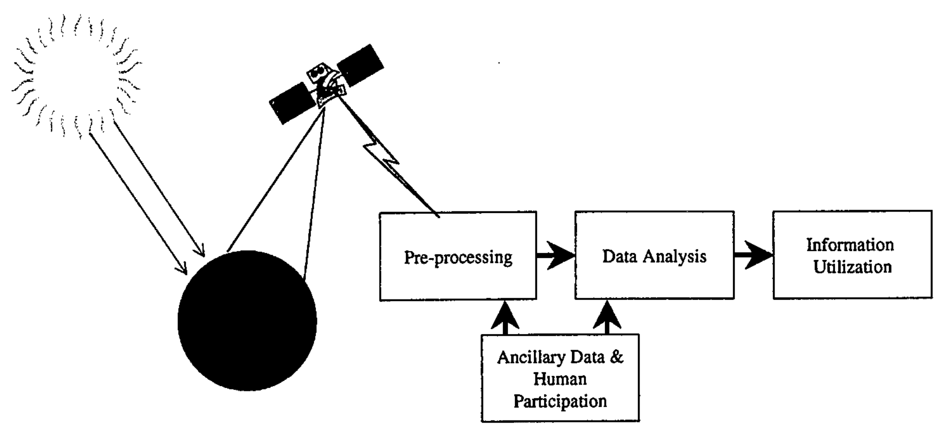

Figure 22. A conceptual overview of a remote sensing base information system. Adapted from Landgrebe, 1998.

The data provided by the sensor can be examined from three points of view: the image space, the spectral space, and the feature space. The image space offers a spatial, or pictorial, view of the collected data, displaying the geographic relationships of the data samples. Although there is useful information in the spatial view, the limitations of single band (black and white) or three-band (color) imagery do not permit full exploitation of the full data set. The analyst can use the spatial image to label pixels as training samples, or examples of classes of data to be identified. The spectral space is portrayed through graphing pixel content (wavelength against reflectance). Pixels can be identified singly, offering a higher resolution than labeling a group of pixels, which is the level of processing possible in the image space. The feature space contains pixel data across all collected bands. The feature space contains a mathematical characterization of the entire contents of the area represented by a single pixel.

Two methods exist to manage algorithmic processing of spectral data. One is target matching and requires the collection of spectral signatures for each of the constituents in the spectral sample. As time of day, time of year, weather, and other environmental considerations, as well as collection angle, may influence spectral signatures, extensive sampling and library development is necessary to support target matching. In the other method, feature extraction, the analyst views the spatial image and selects areas of interest. The analyst delineates classes that include objects of interest, labels the sample pixels and then trains the system to characterize the spatial image according to the contents of the pixels. The process follows the steps given in Figure 23 below.

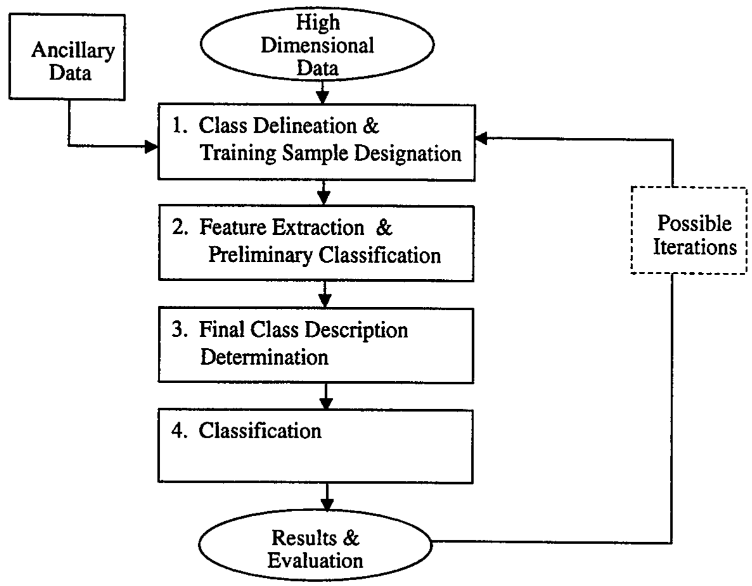

Figure 23. Nominal sequence of steps for the analysis of a hyperspectral data set. Adapted from Landgrebe, 1998.

The system described above shows the relationship between the analyst and the exploitation system. The analyst provides the guidance in selecting objects of interest, and the exploitation system provides the quantification analysis that provides the analyst with an interpretable data set. The timeline for a typical urban feature analysis—carried out on a collection of the Washington, DC Mall and displayed in Figure 24 on the next page—is shown in Table 4 below.

Table 4. Urban Scene Exploitation Activity Timeline

Operation	CPU Time (sec)	Analyst Time (min)
Display Image	18	
Define Classes		< 20
Feature Extraction	12	
Reformat	67	
Initial Classification	34	
Inspect and Add 2 Training Fields		5
Final Classification	33	
Total	**164 sec = 2.7 min**	**25 min.**

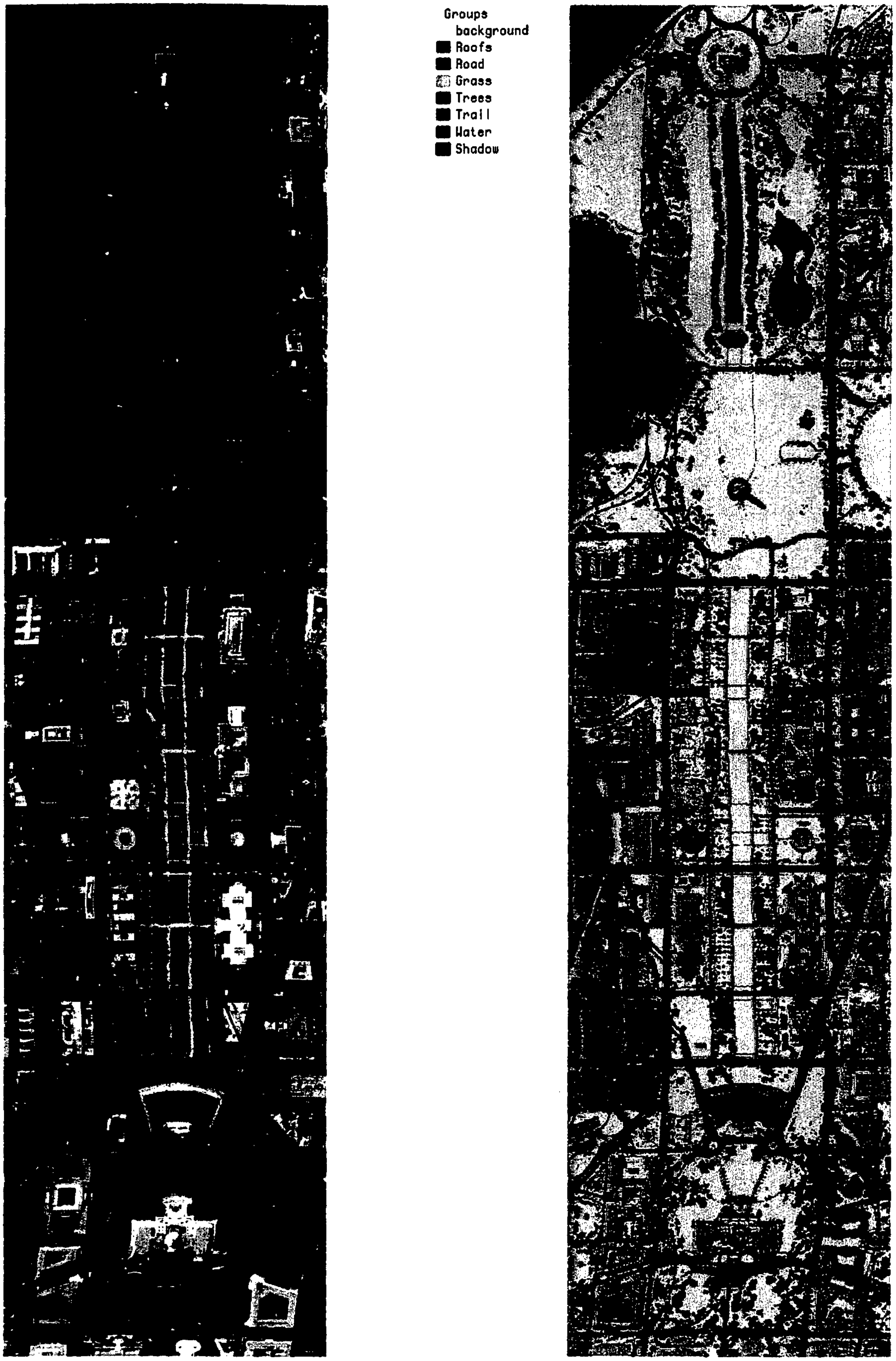

Figure 24. Left: Color IR display ; Right: Color Thematic Map, products of data analysis. From Landgrebe, 1998.

The analytical results pictured above are an example analysis of an airborne hyperspectral data collection flight over the Mall in Washington, DC. Collection was performed in 210 bands in the 0.4 to 2.4-μm region of the visible and infrared spectrum. The data set contains 1208 scan lines with 307 pixels in each scan line and is approximately 150 MB. The steps used in the analysis are briefly described as follows.

Define Classes: The analyst used the Multispec software application program available free from Purdue University. The simulated color (bands 60, 27, and 17 were assigned to red, green and blue, respectively) infrared (IR) photograph was used to determine training samples prior to the composition of the thematic map. Classes chosen were rooftops, streets, grass, and trees. Trails, water, and shadow were also added. As the roofs varied in construction material, and were also similar in content to some of the roads, sets of subclasses were developed to further define characteristics.

Feature Extraction: A feature extraction algorithm, in this case, Discriminant Analysis Feature Extraction (DAFE), was used to calculate a linear combination of the original 210 bands into 210 new features, occurring in order of their discriminative value. The first nine features were determined to be adequate to discriminate between classes.

Reformatting: The newly defined features were the basis for the reduction of the 210-band data set to a nine-band set.

Initial Classification: Once classes and features were defined, the Extraction and Classification of Homogeneous Objects (ECHO) algorithm was run. A maximum likelihood classifier, ECHO segmented the scene into spectrally homogeneous objects and performed first and second order statistical classifications (a multivariate analysis taking advantage of the image's spatial characteristics).

Finalize Training: The initial set was improved by the addition of two more classes, which were added to the training set.

Final Classification: ECHO was run again, using the improved training set, to reclassify the data, providing the Thematic Map on the right side of Figure 23. The entire operation took approximately 25 minutes, of which some 20 minutes was the time the analyst took to determine the classes.

While the feature extraction technique provides an alternative to spectral signature matching, it should be noted that it is still more time-consuming than some operational scenarios can permit. Certainly, it is not the answer for the warfighter, although it shows promise as a tactical tool at the theater level.

Assessment of Operational Requirements

In order to design an effective tactical intelligence spectral exploitation system, it is necessary to determine accurately operational needs for spectral data. Table 5 extracts a sampling of Mission Need Statements (MNS) and Operational Requirement Documents (ORDs) highlighting the official need to exploit spectral data. However, the real question as to the users' needs lies within these general requirements and must be extracted to determine actual user requirements.

Table 5. MNS /ORDs Sample

User Needs	Source		Priority	Applicable System Requirement Definition	Technology Area
	Service	MAP			
Search & Surveillance Capability					
— ***Designated Search Area Capability***	AIP ORD, MNS, ACC	S&R, TMD, SAD		AIP, SYERS P3I, Enhanced U-2, HAE UAV	SAR/EO/IR
— Broad area search capability	ASPO			AIP, SYERS P3I, Enhanced U-2, HAE UAV	SAR/EO/IR
– Capability to cover two 300k x 300k Corps AOs twice a day	ASPO			AIP, SYERS P3I, Enhanced U-2, HAE UAV	SAR/EO/IR
— Wide area surveillance capability	ASPO			Enhanced U-2, HAE UAV	SAR/EO/IR
– Continuous coverage of two 300k x 300k AOs with a 60 second revisit capability	ASPO			Enhanced U-2, HAE UAV	SAR/EO/IR
— Wide Area Search Capability	AIP ORD, MNS, ACC	S&R, TMD, SAD		AIP, SYERS P3I, Enhanced U-2, HAE UAV	SAR/EO/IR
Counter CCDD Capability					
— Detect, locate & ID targets in detail	ACC, ASPO	S&R, TMD, SA/I		AIP, SYERS P3I	MS/HS Sensors, AIP
— MSI for CCDD	ACC	S&R		SYERS P3I	MS/HS Sensors, AIP
Target Development Capability					
— Long range targeting capability to support ATACMS	ASPO			Dark Star, Global Hawk	Platforms, Sensors
— High confidence targeting	ACC	S&R, TMD		AIP, Enhanced U-2	AIP/Platform
— Capability to destroy time critical targets	ACC	S&R, TMD		STS/RTIC/RTS	Sensors
— Improved timelines of targeting decision	ACC	S&R, TMD		STS/RTIC/RTS	AIP, OBP, DRM
— Improved PGM accuracy	ACC, ASPO	S&R, TMD		AIP, SYERS P3I	AIP
— Improved accuracy for targeting & BDA	ACC, ASPO	S&R, TMD		AIP, SYERS P3I	AIP
— High resolution terrain DB	ACC	S&R		AIP	AIP
— Automated cross-cueing between on & off board system	JV2010	S&R			DRM, OBP, Sensors, D/L, GPA, Expl

User Needs	Source		Priority	Applicable System Requirement Definition	Technology Area
	Service	MAP			
Buried/Deeply Buried Target Capability					
— Detect, locate & characterize infrastructure of buried targets	AF Space, ASPO	S&R			MS/HS, Sensors, Proc
Theater Missile Surveillance Capability					
— All weather day/night capability	AFSOC, AF Space, ACC, ASPO	S&R, TMD		Enhanced U-2, HAE UAV	Sensors, DRM
— Precision time critical targeting	ACC, ASPO	S&R, TMD		STS/RTIC/RTS	Sensors, OBP, DRM
— Wide area surveillance capability	ACC, ASPO	S&R, TMD		Enhanced U-2, Sensors, UAV	Sensors, DRM, Platforms
— Detect & track	AFSOC, AF Space, ACC	S&R, TMD		Sensors	Sensors
— Automated detection support tools	ASPO	S&R			OBP, GPA, NRT Expl
— RTS/RTIC support	ACC	S&R, TBM		Enhanced U-2, Sensors	GPA, NRT Expl
— Impact prediction & interception		S&R			Sensors,
Moving Target Capability					
— Long dwell capability	AFSOC, AF Space, ACC	S&R, TMD, SA/I		Enhanced U-2, HAE UAV	Sensors, Platforms, NRT Expl
— Track critical mobile targets	AFSOC, AF Space, ACC			Enhanced U-2, HAE UAV	Sensors, Platforms, NRT Expl
Battle Damage Assessment Capability					
— Improved geo-location for BDA	AFSOC, AF Space, ACC	S&R, TMD, SA/I		AIP, SYERS P3I, DPPDB	Sensors, NRT Expl, Geopsn, GPA, OBP
— Timely collection & BDA analysis	AFSOC, AF Space, ACC	S&R, TMD, SA/I		Sensors	NRT Expl, DRM, OBP, GPA
— Timely dissemination of BDA reporting	ASPO	S&R			NRT Expl, Comms
— Expand BDA capability to all tactical target categories		S&R			NRT Expl, Comms

Search and Rescue Mission Task Analysis

In order to further develop user requirements, a baseline task analysis was conducted to determine what actions occur during the basic spectral analysis process. The initial analysis was based on the premise that the user would employ a principal exploitation tool. A Search and Rescue mission was selected to represent a "typical" mission. The analysis was used to determine points where modifications to the toolset may prove effective to expedite exploitation workflow; an NAIC-trained spectral scientist performed the exploitation activities. Although not included in this report, a task duration was estimated, excluding the sensor collection phase and exploitation requirements generation but including both feature extraction and spectral matching exploitation activities. Because of the variability of sensor collections, the duration ranges were, of necessity, approximate; however, they suited the production of a more information-dense, annotated product than that attempted in the non-military Purdue University example—a contrast in times reflecting the difference in rigor.

Table 6. Scenario Context: Search & Rescue Mission Task Analysis

Task–Find downed pilot.

Pilot ejects from airplane. Emergency message is generated and received by responsible organization.

1. **Responsible organization generates collection requirement. Collection requirement includes:**
    - What type of sensor/platform
    - Where to collect
    - How to view (aspect angle, time of day)
    - Operating altitude
    - Priority
2. **Sensor generates collection data. Data is forwarded to ground station collection agency for preprocessing. Preprocessing includes:**
    - System calibration
    - Conversion of data to specific reference units (e.g., sensors use m^2 or mm^2)
    - Inclusion of header data with raw data set
3. **Pre-processed collection data is forwarded to responsible exploitation organization. Exploitation requirement is generated. Exploitation requirement includes:**
    - Purpose of exploitation
    - Objects of interest
    - Collection specifications
        - Reference location (coordinates) of collected data set
        - Collection sensor type

- Collection sensor look angle
- Collection altitude
- Time of collection

- Responsible organization/Report recipient(s).
  - Response required date and time (NLT ...)

4. Intelligence center receives exploitation requirement attached to collection data.

4.1. Intelligence center assigns analyst(s) to work exploitation requirement.

5. Analyst receives collection data and exploitation requirement.

5.1. Analyst reviews received data and determines level of preprocessing and further processing requirements.

5.2. Analyst ensures geo-reference support data is available for each exploited data set (e.g., GPS/INS data or ground control point location). Cannot proceed if this is not available unless distance to waypoints are sufficient.

5.3. Analyst loads spectral data set.

5.3.1. If no automated data set load routine exists, hand enters data set input parameters into generic load dialog box.

or

5.3.2. Selects appropriate automated data load function.

5.4. Analyst removes bad data (bands, columns, and pixels with zero, erroneous or saturated values).

6. Analyst determines availability of target/features/materials spectral signatures calibrated in reflectance.

6.1. If signatures are available, analyst accesses spectral signatures in existing spectral signature library databases for available materials associated with the downed pilot (clothing, parachute, helmet, life raft, etc.).

otherwise

Analyst skips to Step 10 to perform Anomaly Detection algorithm sequence to find pixels that contain spectral characteristics anomalous to general scene features.

7. Analyst performs atmospheric correction.

7.1. If the analyst has spectral signatures for 3 in-scene materials with different albedo patterns (e.g., calibration panels), analyst applies ELM (Empirical Line Method) algorithm.

or

7.2. If HSI data collection characteristics (collection date, time, collection geometry, and location and altitude) and sensor characteristics (channel response function, etc.) are known, analyst applies the atmospheric correction algorithm, MODH20.

otherwise

Analyst skips to Step 10 to perform Anomaly Detection sequence.

8. Analyst prepares to execute an identification algorithm sequence (a series of related algorithms). **If** the analyst has all necessary information **then** can use the identification algorithm sequence.

otherwise

Analyst skips to Step 9 to perform an advanced identification algorithm sequence.

9. Analyst executes the multi-step advanced identification algorithm sequence for the whole scene, using known material spectral signature (from spectral libraries database).

9.1. Analyst repeats the sequence for each known spectral signature.

10. If no signatures or data characteristics are defined, analyst applies an Anomaly Detection algorithm sequence.

11. Once Anomaly Detection is complete, analyst performs the appropriate identification sequence, repeating steps until all distinct sets of anomalies are identified in named layers.

12. Analyst georeferences data scene.

12.1. Analyst uses GPS/INS information overlay geo-rectified scene on DTED or DEM surface.

12.2. Analyst performs waypoint matching, using ground control points and an n^{th} degree polynomial fitting routine (only gives accurate latitude/longitude estimates for control point locations, especially for locations showing multiple elevation differences).

12.2.1. Enters at least 3 location reference points in dialog box.

13. Analyst generates report(s).

13.1. Analyst exports image as TIFF file into available annotation program (e.g., PaintShop Pro).

13.2. Analyst colors each created layer, designating identified materials and levels of confidence.

13.3. Analyst generates report, including:

- Name of detected/identified materials
- High confidence level identified materials coordinates
- Latitude/longitude lines

- Annotated information on processed data scene (locations by pixel and by layer description)
- Source of data
- Analyst's name

14. Analyst disseminates report(s).

14.1. Analyst sends annotated TIFF file, with accompanying text file (if any) to requester.

Figure 25 on the next page shows the high level activity flow chart developed to depict the Search and Rescue mission task analysis. Algorithmic sequences work on a single band at a time, so depending on the bands of interest, iterations of detection and characterization events may vary. Rather than collecting a specific timeline for the preliminary task analysis, the average duration assigned by an experienced spectral scientist was used. While no one-to-one correlation can therefore be made with the feature extraction analysis reported earlier, there is ample evidence to show that neither method is suitable for rapid response targeting requirements. Not only is it clear that automated algorithmic distillation of the spectral data is required to simplify and shorten the analytical task, it is also clear that careful thought and planning must accompany system design such that display screens and exploitation tool sets speed and facilitate the analyst's job rather than creating unintended impediments or adding unnecessary workload (mental, emotional and time stressors).

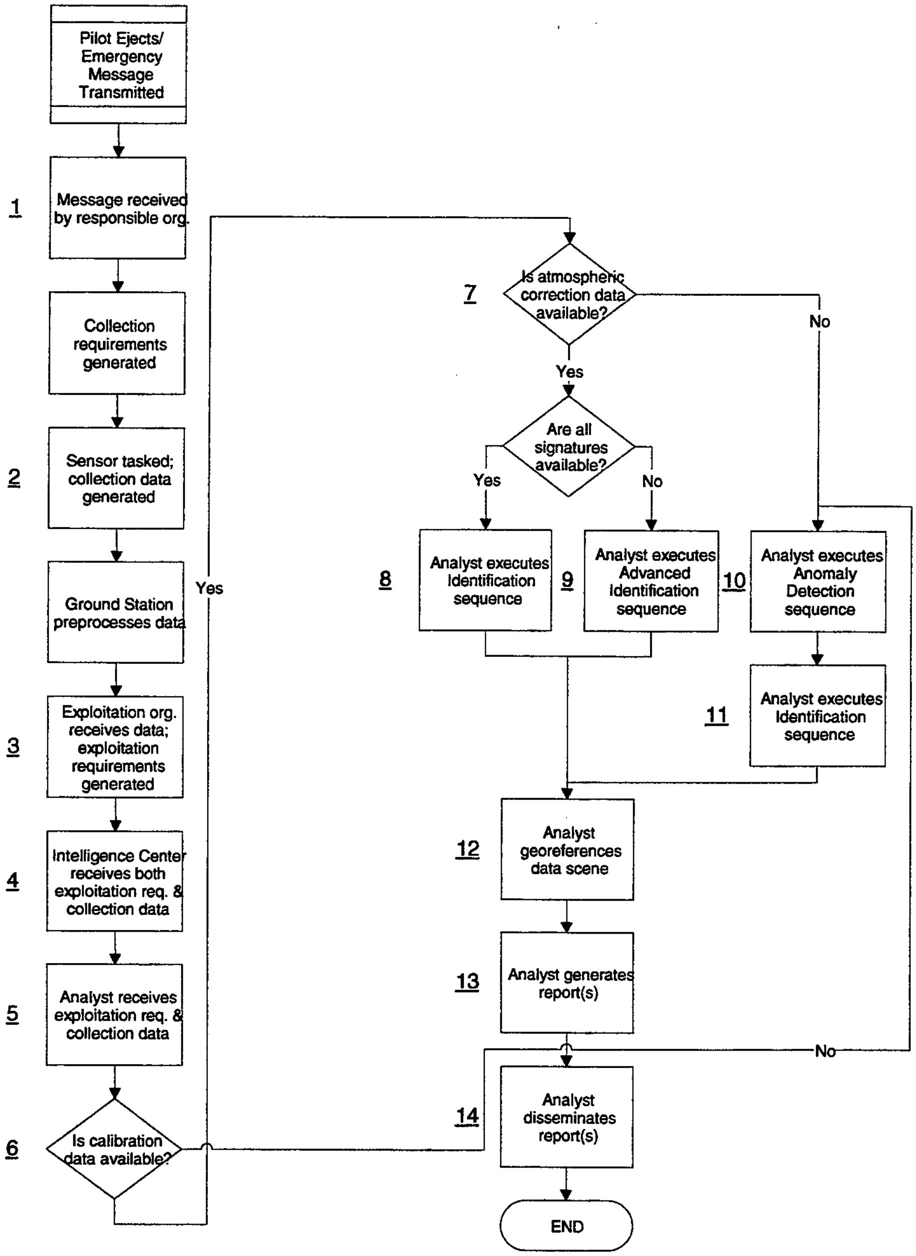

Figure 25. SAR Mission Activity Flow Chart.

Information Overload and Information Presentation

Information overload is a serious problem for analysts of all kinds. The literature search turned up numerous articles discussing analyst overload as a burgeoning problem that dated as far back as the 1970s and since then have only worsened. The spectral analysis scenario given above provides a partial insight into the magnitude of the problem for the spectral analyst. However, not shown were concurrent activities which exploit all source data to support precision responses to operational taskings and which require accessing multiple systems, searching multiple databases, and reviewing the material found therein for relevance and currency. While once the acquisition of the information was the primary difficulty, now the review, interpretation, and report process form the bottleneck. Information order and methods of presentation and data mining strategies, all subjects of current research in civilian applications, are areas of definite concern for the military analyst and must be considered in long term system development in order to offer the optimum exploitation/decision aiding system.

PROPOSED EXPERIMENTAL CONCEPTS

The ultimate goal of this study has been to provide a firm foundation for future efforts to enhance the usability of spectral sensor intelligence by identifying how best to exploit the relationship between spatial imagery and spectral data. Research performed for this study identified the methodology to evaluate (qualitatively and quantitatively) system interfaces and features to support multispectral through ultraspectral exploitation. It is recommended that future efforts employ cognitive engineering techniques, including subject matter expert interviews and empirical test results, to fully develop user-centered system design requirements. Future efforts should be directed toward the design of a spectral data-based decision aiding system, based on innovative spectral technology and applying scientific visualization principles to solve operational problems. The implementation of algorithms to reduce and optimize the number of bands required for visualization display of a particular target of interest will reduce processing and exploitation time. The construction of a fieldable prototype exploitation system will permit high fidelity user testing, including eventual operational deployment for evaluation in a naturalistic setting.

The spectral analysis data collection plan is intended to maximize *pre-design* human factors analysis and promote user requirements-oriented design. The proposed experimental tasks will provide baseline performance standards against which to compare the success of candidate system enhancements, will offer insight into the effects of selected variables on operator performance, and will clarify task-specific user needs. The performance data and collective user requirements will drive design parameters and directly support future military exploitation.

Experimental Design and Data Collection Concepts

The following combination of interviews and experiments are recommended in order to develop a thorough understanding of the users, establish user and exploitation systems baselines, determine system design, test new capabilities, and record the results. The suggested experimental methodology includes subject matter expert interviews administered (ideally) to representatives of the four potential user groups. Additional recommendations include establishment of baseline performance for experienced users and comparison of performance in novice populations. Based on the vision factors identified in this effort, the use of color was selected as the most critical imagery variable to manipulate in initial testing, while manipulation of algorithms was selected as the most important behavioral variable. Subsequent trials manipulating other visual display variables and incrementally moving the experimental test bed from part task software simulations on existing platforms to full task scenarios on a reconfigurable prototype platform in an operational setting are also recommended.

The series of investigative activities is conceived to support system design through capture of user requirements and baseline performance metrics for utilization in candidate enhancement testing and prototype development. Subjects should be drawn from cooperating experts, and ideally, each set of experimental conditions should be run with representatives from each of the four groups in order to capture the both the common and the specific requirements for each type of analysis. A suggested set of areas for further exploration is included.

Interviews

Interviews: The first step must be to ensure that there exists a solid understanding of the users in their operational setting. In order to achieve this, it is recommended that interviews be conducted with subject matter experts. The interviews should help structure the remainder of the experiment by defining current functions, roles, and products. Choices for the other groups vary and should be selected based on both representative qualities and the ability and willingness to allow experimental observation. As no groups are fully exploiting spectral data sets at this writing, some projection will be required.

Establishment of Performance Baseline

In order to build a progressively clearer picture of the interaction of experimental variables in studies of the exploitation of spectral data by the four projected levels of user, baseline performance data should be collected for purposes of comparison against future study results. As NAIC analysts make full use of spectral information as well as spatial information, spectral exploitation baseline development must reflect the application of available processing algorithms. Initial data collection will focus on current NAIC exploitation strategies using available algorithms.

Baseline: Baseline analyst performance data should be collected during a set of target detection simulation tasks. The existing exploitation workstation may be used as a simulation test bed. The parameters for the simulation task should provide for controlled use of pre-determined algorithms in order to gather performance data on specific existing algorithms individually and to facilitate comparison with future test results. The baseline task set should include such typical spectral data exploitation activities as calibration, georectification, anomaly detection, target detection, and target identification and should utilize all typical support capabilities of the exploitation workbench. The measure of merit for algorithm use should be successful task completion. Performance metrics for anomaly detection and for target detection and identification might include response time, accuracy of detection (number of targets noted), and precision of detection (number of targets correctly identified). Workload data should also be captured with each trial set in order to provide a workload baseline. A post-experimental administration of subjective workload evaluations should be conducted after each study set. The capture of behavioral data might include any observable difficulties selecting, invoking, and running the algorithms or interpreting their results.

Comparison of Exploitation Strategies

Comparison Studies: A complete set of comparison studies should be made of experienced users' manipulation of existing exploitation workstation algorithms vs. novice users' manipulations. Real-world task sets, similar to those used for the baseline studies, should be presented to populations drawn from the tactical and operational user groups. All subjects should participate in hands-on training and receive written training materials before participation in the experiment. Novice performance data should be captured and evaluated as described in the baseline investigations. Behavioral data capture is particularly important, as it may indicate possible human-computer interface (HCI) design improvements, or training opportunities to improve novice user performance. The measures of merit and of performance remain the same as described in the baseline activity. Workload data need not be captured in this set of experiments.

After the collection and analysis of baseline performance data for individual spectral data-processing algorithms, other variables should be examined for their contribution to exploitation task performance. In subsequent investigations, the subject population should be presented with similar target acquisition tasks. Potential variables for experimental manipulation include the use of pre-selected algorithms and combinations of algorithms for specific target identification scenarios.

Additional variables of interest include the effect of time stress (such as might be encountered in typical operational activities) on exploitation performance, and the effect of the use of false color combinations to enhance interpretation. The documented importance of color in imagery interpretation and the wide use of false color in spatial exploitation dictates that the application of color combination in false color imagery undergo rigorous examination. As the examples given earlier illustrate, the choice of adjoining colors can produce illusory differences or obscure similarities, thus eliminating the analytical benefits of color-mapping pixels by spectral signatures. The current literature on use of color in displays is not yet complete, nor is it in complete agreement about the efficacy of color combinations. What is clear, however, is that effective use of color has simplified visual search tasks in previous experiments—it can be used to illuminate spectral characteristics and to highlight potential areas of interest. It can also contribute to enhanced text comprehension and can provide a means of inserting data. What is equally clear is that, misused, it can impede both visual search and text comprehension, and can induce visual fatigue and performance errors.

Color Band Map Studies

The controlled testing of the interpretive benefits of color in ultraspectral visual search tasks will identify the most operationally effective uses of color, will identify the cost/benefit relationship of allowing analyst choice, and will capture the ergonomic consequences through both objective and subjective workload measures. It is recommended that initial studies be accomplished through the conduct of three paired sets of experiments. The first paired set would collect baseline data on experienced analysts. Subsequent investigations would repeat the paired test sets for novice users.

Operator Free Choice: In multiple sets of high fidelity, time-constrained search tasks, it is suggested that the analysts be permitted to select color combinations at will. The measure of merit should be target detection performance. The measures of operational effectiveness might be successful detection performance and time to completion for each search task. The recommended physiological measures of ergonomic effectiveness are saccadic and eye blink intervals. Behavioral data capture should include specific color choices and numbers of combinations tried. Post-experimental administration of subjective workload evaluations and subjective preferences should be obtained at the end of each set.

Operator Forced Choice: Based on results of current color utilization research, it is suggested that the same analyst population (not necessarily the same individuals) be presented with the industry-standard optimum color choice(s) for detail discrimination. Performance tests should be conducted and data collected as described above. Data from the forced choice study should be compared with data from the free choice study.

The data collected in these investigations should provide invaluable information on the possible varying levels of complexity of data that, with practicality, may be presented to each of the subject populations. The information derived may be used to direct future development of the exploitation workstation HCI and intelligence products and may even provide critical feedback for strategic planners to guide projected distribution and exploitation of spectral data and spectral data-derived products.

Aiding Studies

After baseline data is collected for each potential user group, further investigations should focus on the utility of visual cue target acquisition aids. Aided target acquisition task variables include both use of target indicators (icons, target boxes, color and luminance highlighting) and the use of confidence level coding (color-coded, numerical, iconic). These investigations should focus on a single enhancement at a time, and should compare aided performance with baseline performance using value analysis, a two-tiered evaluative process (developed by AFRL's Human Effectiveness Directorate; Eggleston & Kulwicki, 1984) that refines the list of candidate enhancements during structured testing. Aided performance data should be collected in the course of part task simulations under the circumstances detailed in the Color Band Map Studies, capturing performance, workload and behavioral data in the manner described.

Exploitation Tool Concept Development

Scenario Development

Subsequent to the initial data collection efforts, the second step will be to develop the set of operational scenarios necessary to complete the test procedures. Scenario development will ensure that a set of realistic problems and environments are selected for use in the operational performance evaluation. Several scenarios will be designed, each representing a "typical" mission. It is expected that some experimentation should be performed to validate the software designed for each mission focus, but even if envisioning concurrent development efforts, the initial experimental effort must be a manageable piece of the whole.

Reconfigurable Display Interfaces

It is recommended that a series of part task studies, using both currently configured software and incorporating concept display interfaces, follow scenario development. The concept development phase of experimentation should use the information obtained in the activities above to build a progressively clearer picture of the interaction of experimental variables. In studies of the exploitation of spectral data by the projected levels of user, baseline performance may be collected using experienced analysts. The parameters for the simulation task should provide for controlled use of pre-determined algorithms in order to gather performance data on specific existing algorithms individually and to facilitate comparison with future test results.

Following the establishment of a performance baseline, it is recommended that several different prototype screens and features be developed for testing. Figure 26 provides a sample artist's rendering of one such screen. In this screen capture, the targets of interest are naval ships; upon display of the image, one pre-selected color is used as the target identifier. In the example, the ships are displayed in red to indicate they are potential targets. This display provides a single button or keystroke identifier for optimal display of area of interest and could eliminate multiple time consuming functions currently employed in exploitation (i.e., anomaly detection, signature analysis, etc.).

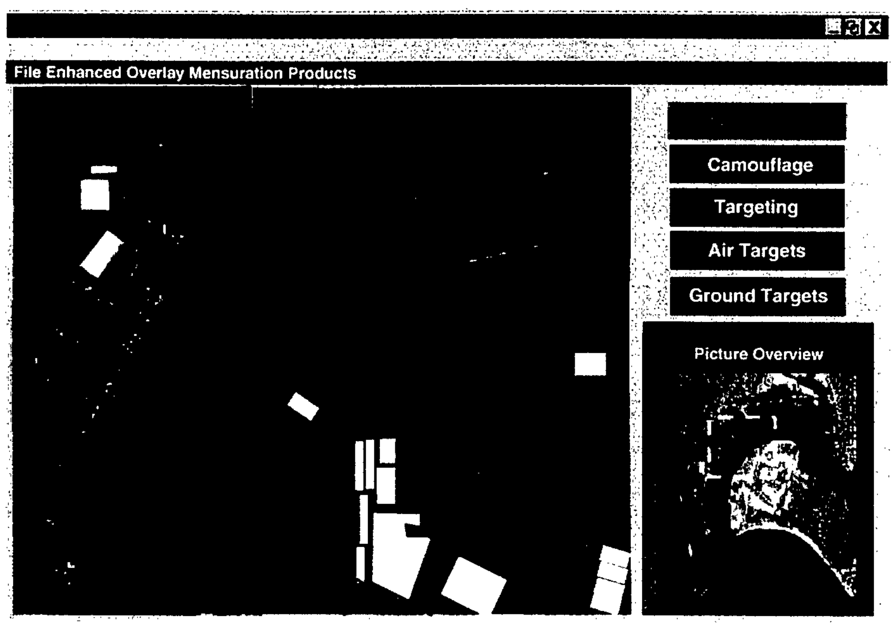

Figure 26. Artist's rendering of a sample screen.

Prototype Development

The preceding investigative results are envisioned to form the basis for the development of a prototype spectral data exploitation system. It is currently envisioned that the system retain existing capabilities, such as current algorithms and algorithm sequences, but that it should integrate several additional commercial-off-the-shelf technologies. It is recommended that the system be based on ENVI™, a commercial spectral exploitation product that supports rapid developmental prototyping in an interactive data language (IDL) environment. Another set of spectral exploitation tools that should be considered for incorporation into the prototype system is produced by Applied Analysis, Inc. (AAI). The AAI toolkit includes adaptable software for the identification of optimal discriminant spectral bands and can be used to distill the information in a spectral data cube into a manageable data set. The initial concept anticipates the system preprocessing one or two 3-band combinations. The data display would be compiled to support the best viewing parameters for the analyst. This should be determined in the experimental phase. There are multiple approaches to configure the optimal display, including the presentation of a standard color mapping, the changing of color spectrum and the application of a reference key, and these or any others that prove fruitful during experimentation, should be incorporated into the prototype system. The system, as envisioned, will produce displays that support the analysts' basic targeting needs, (i.e., rapid identification of areas that may contain targets). It is projected that the initial system would not only contain spectral tools, but also include baseline imagery functions like mensuration capabilities to aid the analytical functions. The production system should support rapid reporting procedures, georectification, and collection tasking.

Field Experimentation

It is recommended that future field analysis efforts be performed in full task scenarios in actual tactical operational environments.

Once the "best performers" among the candidate concept displays and configurations are incorporated into a prototype spectral exploitation workstation, the prototype should be field-tested in several operational locations. The investigative team should conduct in-briefings to key personnel and SMEs; briefing materials should include why the experiment is needed, who is required to participate, what we expect to achieve, and time required. The team should, at minimum, comprise three research professionals: a human factors expert to moderate and observe experimental procedures, a software engineer to overcome any system problems, and functional expert to monitor activity and answer technical questions.

After the initial in-brief the SMEs should receive training on the new prototypes and techniques, as well as on the scenarios employed. As in the earlier experiments, the MOE and MOP data should be based upon mission accomplishment, with performance factors including time and accuracy. Relevant data should be captured through input device monitors and observational recordings. To the degree possible, the data collection should be unobtrusive to the SME. At some point after the in-brief, SMEs should be selected for personal interviews during which knowledge elicitation techniques will be used to capture subject expertise. A "hot wash" of the experimentation should be done and feedback to the supporting organization be provided (disclosure of initial findings) and the supporting organization should be afforded the opportunity to comment on the experiment report prior to its official release. Upon returning from the experimentation site, in-depth analysis of the results, including organization comments, should provide a set of validated user requirements for an effective tactical intelligence spectral exploitation workstation.

The experimental methodology described above is designed to directly support operational fielding of spectral exploitation tools, define new spectral products for all three levels of visualization needs and help define new user requirements for spectral sensor design. Besides those projected results, supplementary benefits may accrue—the information derived may determine new operational CONOPS and drive sensor employment issues. Additionally, the recommended studies will provide baseline performance data on the operational utility of commercial toolset visualization products and displays. Certainly, organizations participating in such studies should gain both a valuable understanding of advances in spectral analysis and an awareness of current system inadequacies for projected exploitation.

FUTURE RESEARCH OPPORTUNITIES

Areas of Investigation

The preliminary studies should significantly advance knowledge of the human factors issues involved in the use of spectral science for tactical implementation. However, there remain rich opportunities for further investigation. Continued development of the prototype exploitation workstation that forms the test bed for the proposed investigations should be supported by human factors-oriented experimentation and cognitive engineering methodologies. The results will guide the design of a field-testable prototype that will provide both optimally designed interfaces for the four potential user groups and tailorable products.

The following is a short list of potential research issues for spectral data exploitation workstation display design. Some issues relate to the visual capabilities of the user, while others involve investigations regarding the organization and presentation of the spectrally derived data. Any or all of these issues' effects may impact performance. If imagery exploitation products are sent in imagery-based formats, then these issues may apply equally to operational product recipients.

1. Complexity of presentation of information from multiple bands
   - Multiple views in simultaneous, fixed-format presentations
   - Multiple views available on demand in 1) simultaneous or 2) sequenced presentations
   - Mixed "media" (imagery, graphic, tabular, audio, ticker data displays. etc.) in fixed format presentations
   - Mixed "media" presentation (imagery, graphic, tabular, audio, ticker data displays. etc.) on demand in 1) simultaneous or 2) sequenced presentations
2. Normalization of image to prevent display saturation
3. False coloring of fused images for image segmentation and target recognition
4. Zoom, perspective, and orientation alteration capabilities
   - Effects on ability to self-orient with respect to image
   - Visual disturbances
5. Chromatic differences (effect on ability to see detail)
6. Luminance differences (effect of enhancement or removal of visual cues)
7. Target detection in embedded displays
   - Contrast differences (target against field)
   - Contours/edge detection

- Texturing within image (either sensor processing artifact or visual effect of patterns formed within image)
- Target orientation (shape alteration/distortion)

8. Coding issues in aided target search
    - Luminance cues
    - Chromatic cues
    - Shape/symbol cues
    - Flashing cues
    - Use of complex, multiple coding schemes
9. Visual fatigue due to color combinations, variable luminance, flashing or shape-coding techniques, detailed visual search tasks
    - How many breaks required to maintain attentive state?
    - How long should breaks be to be effective?
10. Diurnal and seasonal changes in imaged locations (effects on target search/recognition strategies)
11. Selection of optimum information presentation methods for different types of information
    - Advanced graphing and histogram techniques
    - 3-D vs. 2-D presentations
12. Optimal information organization for information retrieval
    - Organization and presentation of data available from spectral data sets
    - Organization and presentation of historical/supporting data
    - Data mining strategies
    - Retrieval strategies

CONCLUSION

The analytical methods used with spectral data divide between analysis of spatial and analysis of spectral data. In both commercial and military applications, the current analytical process relies heavily upon the actual quantitative spectral data collected by the sensor. The collected data is accessed both through individual spectral graphs, which chart spectral returns for designated portions of the scene, and through pictorial representations, in which the constituent particles' spectral composition are assigned on a pixel-by-pixel basis to the spatial representation of the scene. In all cases, analysis is heavily dependent upon existing algorithms to classify, quantify and rank the frequency of occurrence of specific returns, and to present that information either graphically (in charts) or pictorially (in thematic maps).

Problems inherent in the application of current analytical techniques to military missions are primarily based on time constraints imposed by the complexity of the process and the multiplicity of steps required. The information content of a spectrographic collection return is nothing less than phenomenal. However, while data can be mined at the pixel level, single pixel spectrographic presentations can only identify components within an area of interest; they do not show locational relationships nor do they show frequency or density of occurrence within the imaged area. In order to achieve a sense of the distribution of targets of interest, the analyst must run multiple algorithms, assign means of identification and review multiple pictorial displays. Using currently available methods, analytical duration is too lengthy to permit the use of spectral data analysis for rapid targeting.

Ultraspectral imaging spectroscopy is as yet an immature technology; development programs for both collection and exploitation techniques are high profile and receive strong financial support. However, the insufficient funding assigned to the development of user-centered exploitation systems has evoked concern at the highest levels of DoD. The lack of appropriate exploitation tools seriously impedes the ability of the military to obtain full value from the burgeoning spectral intelligence collection capabilities. The intelligence analyst, swamped by the rain of available data, suffers from what the French call an *embarras de riches*, in that the data available is greater than the intelligence community's ability to process it. A series of news reports in both the print and broadcast media created a small firestorm early this year when they described the temporary loss of service over New Year's weekend of several intelligence-gathering satellites among the nation's collection assets. More worrisome than the actual communication breakdown, which was of relatively short duration and affected only some of the sensor systems, was the admission by senior DoD officials that the loss was unimportant, as under normal circumstances our intelligence gathering far outstrips our intelligence processing abilities. As was observed in the *Chicago Tribune's* January 13th and 14th articles (which painted a disturbing picture of the overloaded analyst struggling to review available imagery for possible terrorist activity), it is difficult to confidently assess whether one has lost something valuable if one doesn't actually see what is lost. The *Chicago Tribune* reports also noted the chronic underfunding of analyst exploitation tool development in favor of funding ever more sophisticated sensor technology, to which the DoD sources attributed our unprocessed information glut.

Funding difficulties notwithstanding, there are numerous operational requirements that spectral data must support. Each requirement is accompanied by an equally large number of complicating factors: the modern warfighter is committed to "no" or few casualties, increased accuracy, and limited collateral damage. Within these constraints, the warfighter faces diminishing reaction timelines, complex targets, advanced concealment techniques, and high threat environments. Within seconds or minutes of initial information receipt, the warfighter is expected to ingest voluminous amounts of data and produce an accurate firing solution that places weapons within meters of a target. All of these factors have significant impacts on tactical decision makers, from commanders to pilots, gunners, weapons system operators, and analysts. The stresses imposed by modern warfare affect human cognition in areas from decision-making processes to response time to accuracy of response. Therefore, it is imperative to provide the right information at the right time in the right format. How can that objective be met?

Any review of system acquisition programs will support the necessity to capture user requirements early and to capture them well. The literature is replete with examples of engineering processes that would have benefited from the early implementation of human factors and cognitive engineering principles. Many systems, developed in the hope that they would meet a critical need, have either been rethought and redesigned at unnecessary additional expense or have been sidelined due to inadequacies that were all too foreseeable. The waste of funds and the impairment of mission readiness due to delayed deployment are unacceptable in the current climate. Shrinking forces and shrinking budgets coupled with growing global responsibilities and rapid response requirements indicate the necessity to plan ahead and plan well. The analyst's need for effective tools to harness the power of spectral science is both clear and urgent. The means to design effective tools are within our grasp. The need to apply the best design process in order to produce the best product demands the application of human factors and cognitive engineering processes in spectral exploitation system design.

The review of visual psychophysics and other software design human factors issues conducted for this effort, as well as the examination of the state-of-the-art spectral imaging systems, illuminated a number of vision-related considerations in the design of a tactical spectral exploitation workstation. Of the visual issues that demonstrate potential to impact analyst performance, either positively or negatively, the use of color stands out as the single most important factor. Both in its use in thematic mapping and its use in ATC and ATR coding schemes, color can enhance or impede the analyst's task. Luminance differences inherent in display colors impact their effectiveness as target cuers and their intelligibility as target identifiers. Color contrast effects, including edge detection and magnitude determination interference; discrimination difficulties; unintended stereopsis effects; visual processing delays; and visual fatigue are induced by poorly chosen or overabundant chromatic juxtapositions. All of these issues underscore the importance of chromaticity to on-screen target search presentations. In the design of future tactical intelligence exploitation systems—if use of scene analysis is to benefit the short turn-around of rapid targeting applications—chromatic functions form the critical area to which experimental consideration must be given.

A host of other issues include the relative merits of coding schemes (size, shape, luminance, color, etc.) which are considerations in the design of ATC and ATR enhancements and control for visual effects caused by intensity variance in contours and edges; and the determination of functions best suited to quantification, distillation, classification/identification and fusion algorithms and the further development and testing of such algorithms to reduce/refine the data, capture the relevant information, and present it in the most accessible form. Additional documented concerns, such as increased workload (induced by either over dependence on mental fusion of available data or by unwieldy, labor-intensive software applications); visual fatigue and impaired focus (due to hours of continuous inspection of visual displays); and important issues of information organization and presentation order are barely mentioned in this report—just noted to ensure that due consideration is given to the range of psychophysical issues which need investigation and eventual resolution before the design process is too far advanced to correct possible mistakes.

Extensive, early collection of user requirements, coupled with a rigorous preliminary testing of the concepts prior to prototype development, as suggested in this report, will ensure the completed prototype is a springboard for innovative solutions to the challenges encountered in the military spectral exploitation domain. It will lay the groundwork for new spectral exploitation systems designed to support the operational user and the distributed command decision-making process. Additionally, it will serve as a much-needed test bed to study the projected benefits of innovative spectral analysis techniques. This test bed has the potential to augment AFRL research projects for the next 5-10 years. Already numerous operational understanding and usability shortfalls have been identified as high potential and high dividend research opportunities. When the prototype unit is proven successful and operational timelines are effectively reduced, the fielding of tactical intelligence workstations will fill an immediate need extant in the operational community.

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ACRONYMS

ACTD	Advanced Concept Technology Demonstration
AFRL	Air Force Research Laboratory
ANSI	American National Standards Institute
ATR	Automatic Target Recognition
AVIRIS	Airborne Visible/Infrared Imaging Spectrometer
C2	Command and Control
CARS	Contingency Airborne Reconnaissance System
CCDD	Camouflage, Concealment, Denial, and Deception
CONOPS	Concept of Operations
COSMEC	Common Spectral MASINT Exploitation Capability
DAFE	Discriminant Analysis Feature Extraction
DoD	Department of Defense
ECHO	Extraction and Classification of Homogeneous Objects
EO	Electro-Optical
EUCOM	European Command
GSD	Ground Sampling Distance
HCI	Human-Computer Interface
HSI	Human-System Interface
HSI	Hyperspectral Imagery
HYDICE	Hyperspectral Digital Imagery Collection Experiment
IA	Imagery Analysts
IDL	Interactive Data Language
IR	Infrared
IRARS	Image Resolution and Reporting Standards Committee
JAC	Joint Analysis Centers
JIC	Joint Intelligence Centers
JISE	Joint Intelligence Support Element
JPL	Jet Propulsion Laboratory
JTF	Joint Task Forces
MASINT	Measurement and Signatures Intelligence
MNS	Mission Need Statements
MOE	Measure of Effectiveness

MOP	Measure of Performance
MS IIRS	Multispectral Image Interpretability Rating Scale
NAIC	National Air Intelligence Agency
NASA	National Aeronautics and Space Administration
NMD	National Missile Defense
ORDs	Operational Requirement Documents
P3I	Pre-Planned Product Improvement
P_k	Probability of Kill
RPT	Rapid Precision Targeting
SRC	Stimulus-Response Compatibility
SYERS	Senior Year Electro-optical Reconnaissance System
TES	Tactical Exploitation System
TM	Thematic Mapper
USGS	United States Geological Survey
USI	Ultraspectral Imagery